ELEMENTS OF INDUSTRIAL HEAT

VOLUME I

ELEMENTS OF INDUSTRIAL HEAT

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PREFACE

THE purpose of this book is to present the fundamental principles of heat engineering in a clear and readily understandable manner.

The material in the book has been successfully presented for several years to students of widely varying latent abilities, and has been used for both group and individualized instruction. In general the mathematical discussion has been kept at a minimum, and the language is as simple as a book of this character will permit. Only such technical words and phrases are introduced as seem necessary to enable the student to feel at home in a technical atmosphere, to understand current technical literature, and to handle standard references with confidence.

The first chapter discusses the fundamental relations between heat, mechanical, and electrical energy. Chapter II deals with the measurement of quantities of heat, that is, with calorimetry. The effects of heat in producing expansion and contraction of solids, liquids, and gases are considered next. Following this comes a rather comprehensive and somewhat rigorous study of the effects of heat in producing changes in state. Chapter V introduces the practical subject of steam calorimetry primarily to serve as material to test the student's knowledge of the properties of steam studied in the previous chapter. The transmission of heat by conduction, convection, and radiation; a study of the physical properties of fuels and their combustion; and a brief insight into the field of household humidification complete the first eight chapters of the book. The remaining section, Chapter IX, is presented in order to introduce to the student a few of the elementary principles of thermodynamics.

At the end of each chapter there is a brief summary of the material presented in the chapter and a set of review problems for solution. A complete set of drill problems for the entire book is to be found in Appendix A. These problems are arranged, for

the most part, in such a way as to break down difficult conceptions into a series of easy steps. The problems in Appendix A are numbered with both a numeral and a letter. The numeral designates the article in the text where the information about the problem may be found; the letter is used to grade the problems with respect to difficulty.

The authors wish to take this opportunity to express their indebtedness to the following persons, all of the Rochester Athenæum and Mechanics Institute, who have aided both by their contributions and by their constructive criticism: F. H. Evans, formerly Head of the Mechanical Department; Herman Martin, present Head of the Mechanical Department; E. H. Lang; R. Weller; L. A. Marriott; Elva Lyon; and G. E. Barton, Jr.

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The authors will welcome suggestions or criticisms that will increase the usefulness of the book or corrections that will make the book more accurate.

J. A. R.
J. W. G.

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ELEMENTS OF INDUSTRIAL HEAT

CHAPTER I

FUNDAMENTAL CONCEPTS

1. Foreword.—The material set forth in this text is intended to develop a good preparatory knowledge of heat engineering to serve as a background for further study in this field. The first chapter is devoted to the study of fundamental principles which must be thoroughly mastered to make possible a complete understanding of the technical situations involving a knowledge of heat.

2. Nature of Heat.—The generally accepted theory of the nature of heat is mechanical in character. All substances are considered as being composed of very small particles, called molecules. These molecules are always in motion.[1] The heat content of a body is equal to the combined energies of these moving molecules. The intensity of heat, that is, the temperature, depends directly upon the velocity of the molecules. Thus, as a body is heated, the speed of its molecules is increased. In fact, the rate of vibration may become so rapid that the attraction between the respective molecules will be overcome and the body will undergo a change in shape. This is what happens when a substance changes from one state to another, as for example, from a solid to a liquid, or from a liquid to a gas.

As heat is supplied to a body the temperature of the body rises. Heat which changes the temperature of a body in this way is called **sensible heat.** In other cases, heat may be added without producing any corresponding change in temperature, but instead, produces a change in the state of the body. Heat which produces such a change as this is called **latent heat.**

[1] Molecular motion is believed to cease when the temperature of the substance is reduced to −460 deg fahr.

3. Temperature.—Temperature is a representation of the rate of molecular activity within a body, and is an indication of the **intensity of heat** present. If the rate of molecular motion is low, the body will be at a low temperature; if the

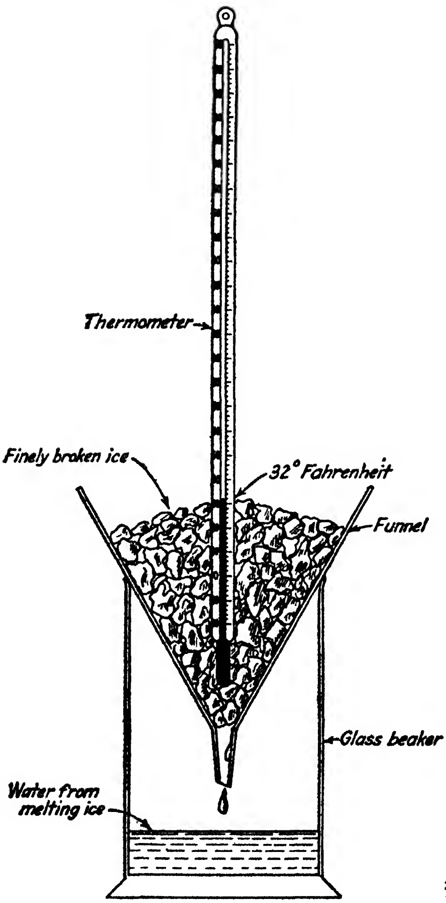


Fig. 1.—Determination of freezing point.

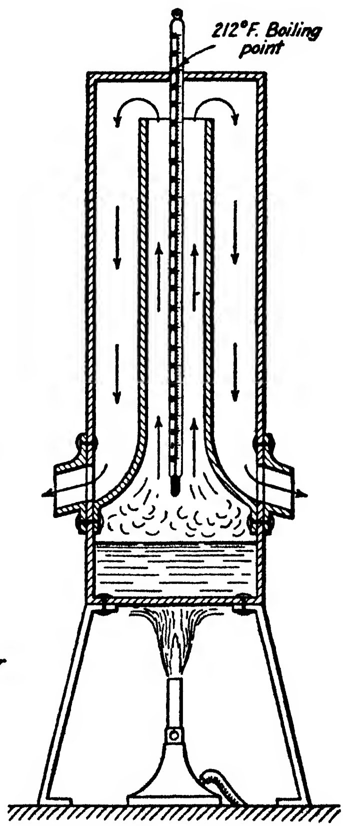


Fig. 2.—Determination of boiling point.

molecules move rapidly, the body will be at a high temperature. Hence the temperature of a body is determined by the speed of its molecules.

When a body is capable of transferring heat to another body,

it is said to be at a higher temperature than the second body. If two bodies are at the same temperature, the transmission of heat from one body to the other is impossible. Thus *temperature may be defined as the heat condition of a body which represents its ability to transmit heat to other bodies.*

4. Temperature Scales.—In American engineering practice, temperatures are usually measured on the **Fahrenheit** temperature scale. The degree divisions on the Fahrenheit thermometer are obtained as follows: The bulb of the thermometer is first placed in melting ice as shown in Fig. 1, and the point at which the mercury remains stationary is labeled on the stem as 32 degrees. Next the bulb of the thermometer is surrounded by steam formed from the boiling of water under conditions of standard atmospheric pressure, as shown in Fig. 2. The height to which the mercury rises in this case is marked as 212 degrees on the stem. These two points (the freezing and boiling points of pure water) are called **fixed points.** The space between them is now divided into 180 equal divisions, called **degrees.** Degree divisions of the same length as those between the fixed points are extended both above and below the 212- and 32-degree marks.

In scientific investigations a **Centigrade** thermometer is used. The essential differences between the Centigrade and the Fahrenheit thermometers are in the marking of the fixed points and in the number of degree divisions between the fixed points. On the Centigrade thermometer the freezing point is marked 0 degrees, and the boiling point is labeled 100 degrees. The distance between these two fixed points is divided into 100 equal divisions called degrees Centigrade, and these degree divisions likewise are extended above and below the fixed points.

5. Relation between Centigrade and Fahrenheit Temperatures.—The comparative facts concerning the two temperature scales in common use are shown in the table below:

	Abbreviation	Freezing Point Number	Boiling Point Number	Difference between Fixed Points
Fahrenheit........	fahr	32 deg	212 deg	180 deg
Centigrade........	cent	0 deg	100 deg	100 deg

Fig. 3 shows a Fahrenheit and a Centigrade thermometer placed side by side with their corresponding fixed points opposite each other. If both thermometers are exposed to the same temperature, the height of the mercury column in each thermometer will be at the same distance above the freezing point. This fact will be readily seen by referring to the figure.

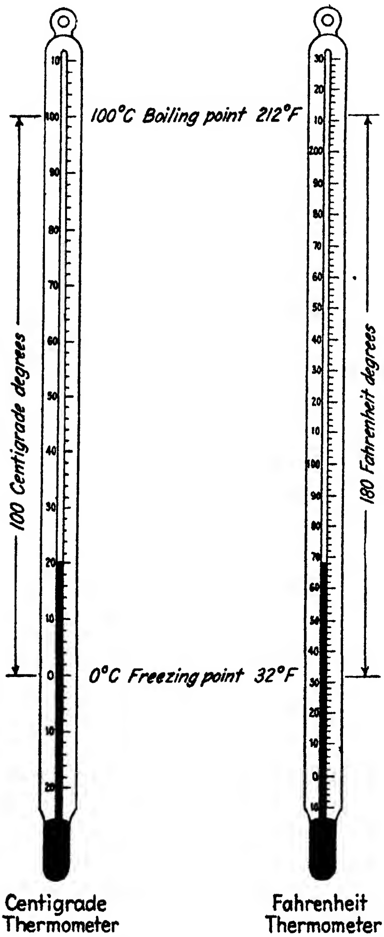


FIG. 3.—Relation between a Centigrade and a Fahrenheit thermometer.

Since the distance between the fixed points on the Centigrade scale is divided into 100 equal divisions, while the same distance on the Fahrenheit thermometer is divided into 180 equal parts, it follows that 1 degree Centigrade will equal $\frac{180}{100}$ or $\frac{9}{5}$ of a degree Fahrenheit, or 1 degree Fahrenheit will equal $\frac{100}{180}$ or $\frac{5}{9}$ of a degree Centigrade. Then we may say:

1 degree Centigrade
$= \frac{9}{5}$ of a degree Fahrenheit.
1 degree Fahrenheit
$= \frac{5}{9}$ of a degree Centigrade.

When the reading of a temperature from one thermometer scale is to be transformed into the equivalent temperature reading on the other thermometer scale, the differing value of the freezing point must be taken into account, as well as the different values of the degrees. We can see from an inspection of Fig. 3 that when the Centigrade thermometer reads 0 deg cent the corresponding reading on the Fahrenheit thermometer is 32 deg fahr. Now, if the Centigrade thermometer reads 10 deg cent, then the equivalent

Fahrenheit thermometer reading would be $32 + (10 \times \frac{9}{5}) =$ 50 deg fahr. Likewise, if the Centigrade thermometer reads C deg cent the equivalent Fahrenheit temperature reading would be $32 + (C \times \frac{9}{5})$.

From the above we may state:

$$F = 32 + (C \times \tfrac{9}{5})$$

or in a form easier to remember,

$$\frac{C}{5} = \frac{F - 32}{9} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (1)$$

in which F = Fahrenheit thermometer reading, deg fahr.
C = Centigrade thermometer reading, deg cent.

Example 1.

How many degrees Fahrenheit is 20 deg cent?

Solution.

20 deg cent = 20 Centigrade degrees above freezing point.
20 deg cent = $(20 \times \frac{9}{5})$ = 36 Fahrenheit degrees above freezing point.
20 deg cent = 36 + 32 = 68 Fahrenheit degrees above Fahrenheit zero point.
Therefore 20 deg cent = 68 deg fahr.

Example 2.

How many degrees Centigrade is 122 deg fahr?

Solution.

122 deg fahr = (122 − 32) = 90 Fahrenheit degrees above freezing point.
122 deg fahr = $(90 \times \frac{5}{9})$ = 50 Centigrade degrees above freezing point.
50 Centigrade degrees above zero point = 50 deg cent.
Therefore 122 deg fahr = 50 deg cent.

6. Limits as to Usage of Mercury Thermometer.—The practical range of usage for the ordinary mercury thermometer is from −31 deg fahr to 580 deg fahr, since under conditions of normal atmospheric pressure mercury freezes at −37.8 deg fahr and boils at 598 deg fahr. However, if the space above the mercury in the thermometer stem is filled with a chemically inert gas, such as nitrogen, the thermometer may be used for measuring temperatures as high as 1000 deg fahr. In all cases where the thermometer

is to be used for the measurement of high temperatures it is necessary to construct it out of quartz instead of glass since the glass will soften at temperatures around 1100 deg fahr.

7. Pyrometers.—It is customary industrial practice to employ a pyrometer when measuring temperatures exceeding 500 deg fahr. The most common types of pyrometers are as follows:

1. Thermoelectric couple.
2. Optical pyrometer.
3. Radiation pyrometer.
4. Seger cones.

8. Thermoelectric Couple.—Fig. 4 shows a **thermoelectric pyrometer** which consists of two thermocouples, a milliammeter,

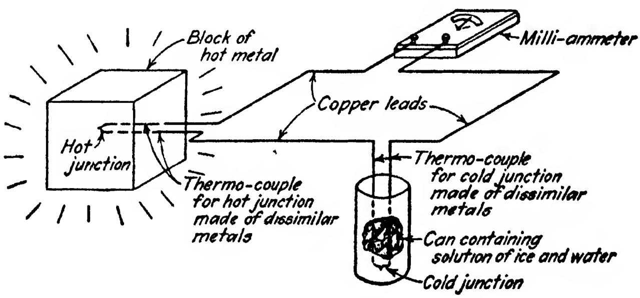


Fig. 4.—Diagram showing method of determining temperature of a block of metal by means of a thermo-electric pyrometer.

and suitable connecting wires. The thermocouples are constructed of two heavy wires of dissimilar metal, welded together at one end, but otherwise insulated from each other by porcelain tubing. When in use, the free ends of the thermocouples are connected to a milliammeter in the manner shown in the figure. The welded joint of one of the couples is placed in contact with the object whose temperature is to be determined, and the welded joint of the other couple is immersed in an ice bath, buried in the ground or otherwise held at a fixed temperature. The weld in contact with the hot body is known as the " hot junction " and the other is called the " cold junction."

The action of the instrument is dependent upon the fact that when a difference in temperature exists between the hot junction and the cold junction an electric current will flow in the circuit, which current

is directly proportional to the existing difference in temperature. The milliammeter, an instrument for indicating small electric currents, is in series with the electric circuit and shows the current which is flowing. The meter is calibrated to read in temperature degrees (by comparison with the melting points of known metals). If the instrument is calibrated for a given cold junction temperature, for example, that of melting ice, it will be necessary either to measure all temperatures under these conditions or to apply a correction factor.

For measurements above the melting point of steel, the hot junction thermocouple is usually made with one wire of pure platinum and the other of a platinum alloy. The alloy commonly contains either 10 percent of iridium or 10 percent of rhodium and 90 percent platinum.

9. Optical Pyrometers.—The **optical pyrometer** is used to measure the temperature of incandescent bodies by comparing the intensity of the red light emitted by the body with the intensity of light of the same color from a standard light source in the instrument. By varying the current supplied to the filament of the standard light its brightness is made to match the brightness of the incandescent body. The current flowing through the filament is measured by a milliammeter which is calibrated to read in temperature degrees. The instrument is calibrated by comparison with incandescent bodies of known temperature.

10. Radiation Pyrometer.—When the temperature of a body exceeds 2500 deg fahr it is customary to use a radiation pyrometer to measure its temperature. The **radiation pyrometer** consists of a long cylindrical tube containing a concave mirror at one end and a focusing lens at the other end. The lens is focused on the object whose temperature is to be determined and the rays are passed through the tube to the concave mirror. The mirror concentrates the rays at its focus point where they strike the hot junction of a thermoelectric pyrometer. The temperature reading is obtained in the same manner as with the ordinary thermoelectric pyrometer.

11. Seger Cones.—Furnace temperatures are sometimes measured by placing metal cones of different melting points in the furnace. These cones, called **Seger cones,** are made from the oxide of different metals. Each oxide has a known melting point. A series of these cones are placed in the furnace. The cones having a melting point lower than the furnace temperature will be

fused and will slump down on the plate supporting them; those having a melting point higher than the furnace temperature will not change their shape, and the cones having a melting point equal to the furnace temperature will bend over so that the top of the cone will touch the base plate. In this manner the temperature of the furnace may be determined.

Seger cones are commonly used to measure temperatures from 600 deg fahr to 1900 deg fahr.

12. Measurement of Quantities of Heat.—The unit used in the quantity measurement of heat is the **British thermal unit,** abbreviated Btu. *The Btu is usually defined as the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit.* Owing to slight variations of the thermal properties of water with the temperature, a " mean Btu " is more precisely defined as $\frac{1}{180}$ of the quantity of heat required to raise the temperature of one pound of water from 32 deg fahr to 212 deg fahr. For ordinary calculations of heat quantities involving water, the quantity of heat required to produce a certain change in temperature is found by multiplying the Fahrenheit temperature change of the water by the weight of the water heated. The result of such a calculation gives the amount of heat energy, in Btu, that is required to produce the given temperature change.

Example 1.

Determine the quantity of heat required to raise the temperature of 5 lb of water from 50 deg fahr to 100 deg fahr.

Solution.

1 lb of water raised 1 deg fahr = 1 Btu.
5 lb of water raised 1 deg fahr = 5 Btu.
5 lb of water raised 50 deg fahr = $5 \times 50 = 250$ Btu.

Example 2.

If 200 Btu are supplied to 4 lb of water, what temperature change will result?

Solution.

1 Btu will raise 1 lb of water 1 deg fahr.
1 Btu will raise 4 lb of water $\frac{1}{4}$ deg fahr.
200 Btu will raise 4 lb of water $200 \times \frac{1}{4} = 50$ deg fahr.

In the metric system, the quantitative unit of heat energy is the **calorie,** abbreviated cal. *The calorie is defined as the quantity of heat required to raise the temperature of one gram of water one degree Centigrade.* The calorie is more precisely defined as $\frac{1}{100}$

of the amount of heat required to raise the temperature of one gram of water from 0 deg cent to 100 deg cent.

13. Specific Heat.—*The specific heat of any substance is the quantity of heat required to raise a unit weight of the substance one degree.* That is, the quantity of heat required to raise the temperature of one pound of aluminum one degree Fahrenheit is called

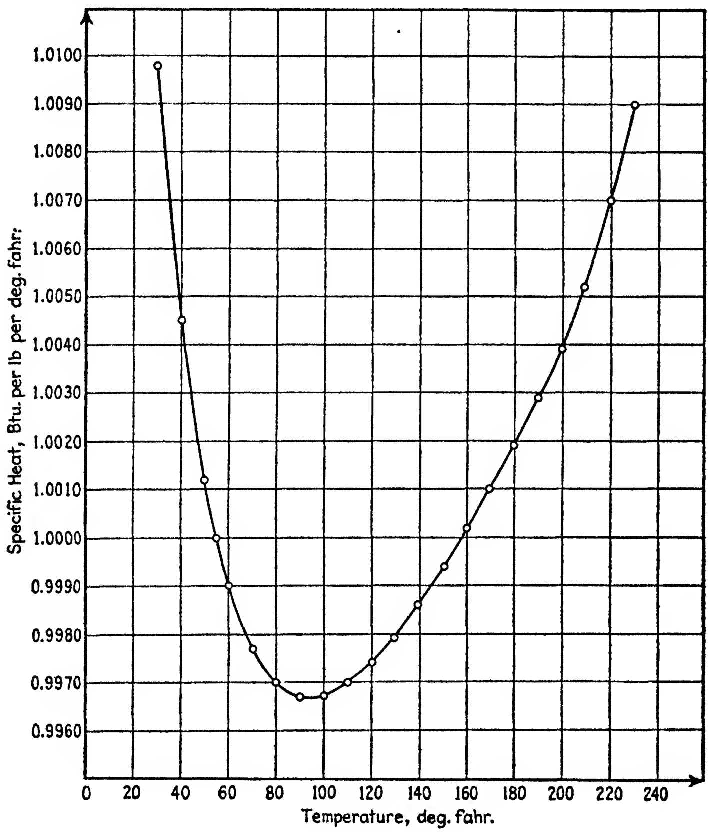


FIG. 5.—Relation between specific heat and temperature of pure water.

the specific heat of aluminum; the heat required to raise the temperature of one pound of lead one degree Fahrenheit is the specific heat of lead, etc.

The specific heat of a substance changes slowly with a change in temperature. For example, the specific heat of water varies as shown in the curve in Fig. 5 between the temperatures of 30 and

230 deg fahr, being unity only at the temperatures of 55 and 158 deg fahr. Hence, there are two recognized values for the specific heat of any material:

(1) The **actual** specific heat at the temperature stated.

(2) The **average** specific heat, which is obtained by taking an average of many of the actual specific heats over a given temperature range.

A few of the average specific heats for some of the more common engineering materials are found in Table I.

Because of the change in volume and pressure of gases with temperature changes, it is necessary to consider two specific heats for gases, namely: (1) the *specific heat at constant volume*, S_v; and (2) the *specific heat at constant pressure*, S_p. This distinction is further explained in Articles 147 and 148 in Chapter VIII.

Example 1.

Determine the number of Btu required to raise the temperature of 10 lb of iron from 70 deg fahr to 500 deg fahr if the specific heat of the iron over this temperature range is 0.113 Btu per lb per deg fahr.

Solution.

0.113 Btu will raise 1 lb of iron 1 deg fahr.

$0.113 \times 10 = 1.13$ Btu will raise 10 lb of iron 1 deg fahr.

$1.13\,(500 - 70) = 485.9$ Btu will raise 10 lb of iron from 70 deg fahr to 500 deg fahr.

Example 2.

A copper vessel weighing 1½ lb has a specific heat of 0.094. What quantity of heat will it absorb if its temperature is raised from 50 deg fahr to 180 deg fahr?

Solution.

Quantity of heat absorbed $= 0.094 \times 1.5\,(180 - 50) = 18.3$ Btu.

Example 3.

What Fahrenheit temperature change will produce a change of 47 Btu in the heat content of 12 lb of petroleum oil? Specific heat of oil, 0.576 Btu per lb per deg fahr.

Solution.

$$47 = 0.576 \times 12 \times \text{temperature change}$$

$$\text{Temperature change} = 47/(0.576 \times 12) = 6.8 \text{ deg fahr.}$$

Table I

SPECIFIC HEAT OF VARIOUS MATERIALS

(Btu per lb per deg fahr)

Substance	Temperature, Deg Fahr	Specific Heat
Alcohol (ethyl)	104	0.648
Alcohol (methyl)	59–68	0.601
Alcohol (methyl)	100	0.590
Aluminum	32	0.209
Aluminum	932	0.274
Aluminum	61–579	0.225
Asbestos	68–208	0.195
Benzine	70	0.451
Carbon	52	0.160
Carbon	1791	0.467
Carbon	3146	0.500
Copper	59–450	0.095
Copper (brass)	210	0.094
Copper	1600	0.126
Copper sulphate	60	0.849
Glass (crown)	100	0.160
Glass (flint)	100	0.116
Ice	0 to −100	0.460
Ice	0 to −20	0.505
Iron (cast)	70–200	0.119
Iron (wrought)	70–200	0.115
Iron	1300–2000	0.214
Lead	60–500	0.032
Mercury	−100–200	0.033
Nickel	50–200	0.110
Oil petroleum	60–130	0.576
Quartz	50–200	0.187
Silver	50–200	0.056
Steel	50–200	0.116
Tin	50–200	0.057
Water	....	1.000
Zinc	50–200	0.095

In studying the method of solution of the foregoing examples, it is observed that the continued product of the specific heat of a material, the weight of the material, and the temperature change

gives the quantity of heat required to produce this temperature change, or more briefly:

$$H = SW(t_2 - t_1) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

in which

H = amount of heat supplied to the material, Btu.
S = average specific heat of material, Btu per lb per deg fahr.
W = weight of material, lb.
t_1 = initial temperature, deg fahr.
t_2 = final temperature, deg fahr.

14. Energy.—*Energy may be defined as the ability to do work.* In our solar system, the major portion of the energy gained by the earth has come directly from the sun in the form of radiant heat energy. Energy exists about us in many forms, for example, as heat energy, chemical energy, mechanical energy, electrical energy, etc. When a body has the capacity to do work it is said to possess mechanical energy, which is expressed in foot-pounds. A foot-pound refers to the amount of energy required to raise a weight of one pound through a vertical distance of one foot, or a two-pound weight one-half foot, etc.

The energy possessed by a body may be of two kinds, namely:

(1) **Potential energy** is energy stored within a body by virtue of its position or deformation. For example, a body that is retained at some distance above the surface of the earth possesses potential energy since it is capable of performing work by falling. The energy stored within a piece of dynamite is potential energy because it has the capacity to perform work when released. Other typical examples of potential energy are presented by a compressed gas, a compressed coil spring, a pendulum at the top of its swing, etc.

(2) **Kinetic energy** is energy possessed by virtue of the motion of a body. The idea of kinetic energy may be illustrated by considering the pendulum in a clock. When the pendulum is at the top of its swing, it possesses potential energy due to its position. As the pendulum swings downward, the potential energy is transformed into kinetic energy producing velocity. When the pendulum is at the lowest point in its swing, all the original potential energy has been converted into kinetic energy, and as a result the pendulum bob has attained its highest velocity. As the pendulum

swings upward again, the kinetic energy is reconverted into potential energy.

Kinetic energy is usually measured in foot-pounds and may be calculated by the equation: K.E. = $WV^2/2g$, in which K.E. = kinetic energy in ft-lb; W = weight of body, lb; V = velocity of body, ft per sec; and g = acceleration of gravity = 32 ft per sec per sec.

15. Work.—In mechanics, work is defined as the quantity which results when the amount of a force is multiplied by the distance through which the force is exerted.

When a person lifts a book from the floor to place it on the table, he does an amount of work equal to the weight of the book (in pounds) multiplied by the vertical distance from the floor to the top of the table (in feet). If the book weighed 1 lb. and the table was 3 ft high, then the person would have done $1 \times 3 = 3$ ft-lb of work. Similarly, if an automobile is towed along a level road with a horizontal tow rope for a distance of 200 ft, the work expended in towing would be equal to the number of pounds' pull on the tow rope multiplied by the 200-ft distance. In both cases a force was applied to an object which produced a movement of the object. These two factors, both **force** and **movement,** must be present, or no work is done in the technical sense of the word.

The amount of work done on an object may be found by obtaining the product of the distance (feet) moved and the force (pounds) *acting in the direction of motion.* This may be stated more briefly as:

$$W = F \times D \qquad (3)$$

in which

W = work done, ft-lb.
F = force applied in the direction of motion, lb.
D = distance moved through, ft.

Example 1.

Determine the quantity of work required to raise a 100-lb bag of cement through a vertical distance of 10 ft.

Solution.

Work = $100 \times 10 = 1000$ ft-lb.

Example 2.

How much work is expended in pumping 210 gal of water to a height of 40 ft?

Solution.

1 gal of water $= 8\frac{1}{3}$ lb.
210 gal of water $= 210 \times 8\frac{1}{3} = 1750$ lb.
Work required $= 1750 \times 40 = 70{,}000$ ft-lb.

Example 3.

A steam locomotive exerts a drawbar pull of 20,000 lb. What quantity of work does it do in traveling a mile?

Solution.

1 mile $= 5280$ ft.
Work done $= 20{,}000 \times 5280 = 105{,}600{,}000$ ft-lb.

16. Power.—Frequently we hear the word power used in the sense that this car is more powerful than that one. Technically, *power is the time rate of doing work*; hence, what is meant, is that the first car can perform the same amount of work in a shorter period of time, or that it will do more foot-pounds of work in the same period of time. The power of a machine would then be expressed as the number of foot-pounds of work that it is capable of doing in a given time interval. From custom, people have formed the habit of measuring power in terms of the amount of work delivered in one second, and therefore power quantities are usually expressed in foot-pounds per second.

For example, if an automobile is towed 300 ft in 4 sec by means of a pull of 350 lb, the power expended to accomplish this result would be $(300 \times 350) \div 4 = 26{,}250$ ft-lb per sec. This may be expressed in the form of an equation as:

$$P = \frac{W}{t} \qquad \qquad (4)$$

in which

P = power required, ft-lb per sec.
W = work done, ft-lb.
t = time required to do work, sec.

Example 1.

What power is required to pump 15,000 lb of water per hour into a storage tank located 35 ft above the pump?

Solution.

Work done $= 15{,}000 \times 35 = 525{,}000$ ft-lb.
Time required to do work $= 1 \times 60 \times 60 = 3600$ sec.
Power required $= 525{,}000/3600 = 145.9$ ft-lb per sec.

Example 2.

A locomotive moving at the rate of 20 miles per hour is exerting a pull of 8000 lb to move its load. What is the power expended?

Solution.

20 mph = 20 × 5280 = 105,600 ft per hr.
20 mph = 105,600/60 = 1760 ft per min.
20 mph = 1760/60 = 29.3 ft per sec.
Hence the train moves a distance of 29.3 ft in 1 sec.
Work done per second, or the power, = 29.3 × 8000 = 234,400 ft-lb per sec.

17. Horsepower.—As the result of a series of experiments conducted by James Watt in England during the seventeenth century, it was estimated that the ordinary English dray-horse could develop approximately 550 ft-lb of work in one second. Hence this unit of 550 ft-lb per sec was arbitrarily chosen as being equivalent to one horsepower, and it has continued in popular usage to the present day. Accordingly, we say that, *whenever work is being accomplished at the rate of 550 ft-lb per sec, one horsepower is being expended.* Hence, the horsepower output of a machine may be found by dividing the power in foot-pounds per second by the number of foot-pounds per second in one horsepower, namely 550. This may be stated as follows:

$$\text{H.P.} = \frac{\text{power developed, ft-lb per sec}}{550} \quad . \quad . \quad . \quad . \quad (5)$$

Example 1.

What horsepower is required to drive an automobile at 30 mph against a total resistance in the direction of motion of 320 lb?

Solution.

$$30 \text{ mph} = \frac{30 \times 5280}{60 \times 60} = 44 \text{ ft per sec.}$$

Power required = 320 × 44 = 14,080 ft-lb per sec.
Horsepower required = 14,080/550 = 25.6 hp.

Example 2.

A lathe cutting tool is exerting a force of 280 lb tangentially to the surface of the piece of circular rod being cut. If the rod is 2 in. in diameter and is revolving at 600 revolutions per minute, what horsepower is required?

Solution.

600 rpm = 600/60 = 10 rps.

$$\text{Work done per second} = \frac{280 \times \pi \times 2 \times 10}{12} = 1465 \text{ ft-lb. per sec.}$$

Horsepower required = 1465/550 = 2.66.

18. Commercial Units of Work.—The unit of work as employed in large work calculations is not the foot-pound, but rather the **horsepower-hour** (hp-hr). *The horsepower-hour is defined as the quantity of work expended by one horsepower in an hour's time.* Therefore, to compute the amount of work done by an engine, it is necessary to have a knowledge of the length of time that the engine runs as well as the horsepower it is delivering.

For example, if a 30-hp engine is operated continuously for 2 hr, 30 × 2 = 60 hp-hr of work will be delivered. If the cost of operating the engine for the 2-hr period was $3.00, then the mechanical energy would have cost 5 cents for each horsepower-hour.

Example 1.

If a 300-hp airplane engine is operated for a period of 2 hr and 40 min: (*a*) How many horsepower-hours of work are expended? (*b*) How many foot-pounds?

Solution.

(*a*) 2 hr and 40 min $= 2\frac{2}{3}$ hr.

Horsepower-hours $= 300 \times 2\frac{2}{3} = 800$ hp-hr.

(*b*) 1 hp = 550 ft-lb per sec.

300 hp = 300 × 550 = 165,000 ft-lb per sec.

Number of seconds of operation $= 2\frac{2}{3} \times 60 \times 60 = 9600$ sec.

Total number of foot-pounds delivered = 165,000 × 9600

= 1,584,000,000 ft-lb.

Example 2.

Water is supplied to a water wheel from a height of 30 ft at the rate of 1200 cu ft per min. If the wheel operates for 8 hr per day, how many horsepower-hours of work are delivered daily?

Solution.

1200 cu ft per min = 1200/60 = 20 cu ft per sec.

One cubic foot of water weighs 62.5 lb.

Weight of water used per second = 20 × 62.5 = 1250 lb.

Work done per second = 1250 × 30 = 37,500 ft-lb.

Total horsepower developed = 37,500/550 = 68.2 hp.

Horsepower-hours delivered per day = 68.2 × 8 = **545.6 hp-hr.**

19. Relation between Heat Energy and Mechanical Energy.—It is well known that *mechanical energy may be changed into heat energy, and heat energy may be changed into mechanical energy.* The heating of the bearings of a machine, the heating of drills and bits in boring, the heating of a piece of wire by successive bendings, the heating of a machine tool being ground are all typical examples of this phenomenon. It has also been established that, whenever mechanical energy is converted into heat energy, a definite quantity of heat is produced for each unit of work done; and, conversely, when work is done by the expenditure of heat energy the same definite quantity of work is produced by each unit of heat energy.

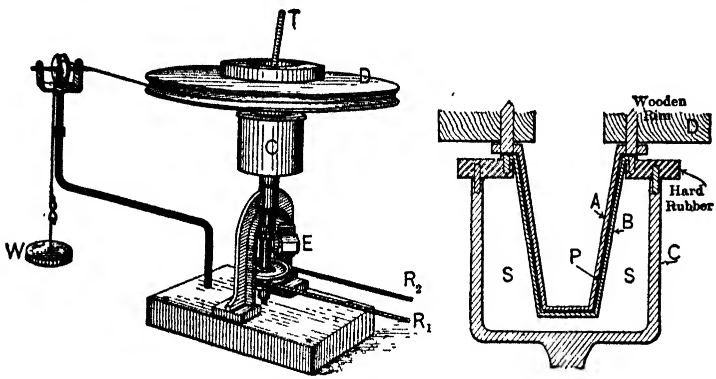


Fig. 6.—Apparatus for determining mechanical equivalent of heat.

The first experiments to determine the relation which exists between heat and mechanical energy were conducted by Joule, and the value arrived at is known as Joule's equivalent. The result of continued experimentation on the part of other investigators showed that one Btu is equivalent to 778 ft-lb. This value is referred to as the *mechanical equivalent of heat,* and may be expressed mathematically as follows:

$$1 \text{ Btu} = 778 \text{ ft-lb.}$$
$$1 \text{ ft-lb} = 1/778 \text{ Btu.}$$

20. Determination of the Mechanical Equivalent of Heat.—The Searles mechanical equivalent of heat apparatus, as shown in Fig. 6, is commonly used in physics laboratories to determine the relation between heat and work units. It is driven by a handwheel

(not shown in the cut) over which the rope R_1–R_2 runs, causing rotation of the cup C. The counter E shows the number of times that the cup C is rotated. The inner cup, A, is not allowed to rotate, but is held back by the counter torque produced by a suitable weight W. This weight is of sufficient magnitude to just balance the friction between the cups A and B. P is a thin sheet of paper introduced between cups A and B to make the friction more uniform.

To operate this apparatus, mechanical energy must be supplied by turning the handwheel to cause rotation of cup C, thus overcoming the friction between the two thin brass cups A and B. The heat generated by this work done against friction is absorbed both by the water which is held in the inner cup A and by the cups themselves. The quantity of heat absorbed equals (weight of water $\times$ temperature change) + (specific heat of cup material $\times$weight of cups $\times$ temperature change).

The mechanical work done against friction equals (pound weight of $W \times$ circumference of pulley D in feet $\times$ number of revolutions of cup C). By equating the work done, to the heat absorbed by the water and cups, the relation between heat and work units is established.

Example 1.

During a determination of the mechanical equivalent of heat the following data were obtained: weight of cups, 0.344 lb; weight of water, 0.0645 lb; specific heat of cup material, 0.094; weight W = 0.543 lb; diameter of pulley D = 1.17 ft, room temperature during experiment, 75.20 deg fahr; initial temperature of water and cups, 61.87 deg fahr; final temperature of water and cups, 88.78 deg fahr; total number of revolutions, 1017. Determine the value of the mechanical equivalent of heat from these data.

Solution.

Temperature difference = 88.78 − 61.87 = 26.91 deg fahr.

Heat developed

= (0.0645 × 26.91) + (0.094 × 0.344 × 26.91) = 2.61 Btu.

Work done = 0.543 × 3.14 × 1.17 × 1017 = 2028 ft-lb.

Hence, 2.61 Btu = 2028 ft-lb.

Then, 1 Btu = 2028/2.61 = 778 ft-lb.

Note: In order to offset radiation losses, the temperature of the water in the inner cup should be as far below room temperature at the

beginning of the experiment as it is raised above room temperature at the end of the experiment.

21. Electrical Energy.—Whenever a quantity of electricity exists, energy is said to be present in the "electrical form." However, the electricity does work only when it is flowing, so we are mainly interested in electric current. The work done by the flow of electricity through a conductor is computed by finding the product of the current, pressure, and time. The usual commercial unit of electrical energy is the **kilowatt-hour,** which equals (amperes) × (volts) × (time in hours) divided by 1000.

The unit of electrical power is the **watt,** which equals the product of the volt and the ampere. The **volt** is the unit of electrical pressure, and the **ampere** the unit of electrical current. A kilowatt, the commercial unit of electric power, equals 1000 watts. When a kilowatt of power is delivered continuously for one hour, one kilowatt-hour of energy is expended. The smaller, or laboratory, unit of electrical energy is the **watt-second,** which is defined as the application of one watt of power for one second of time.

22. Relation between Heat Energy and Electrical Energy.—*Electrical energy and heat energy are mutually interchangeable.* This is evidenced by such everyday examples as the electric flatiron, the electric toaster, electric furnaces for melting ores, electrically welded steel joints, etc. The heat formed in each case is due to the overcoming of an electrical resistance, just as heat is produced mechanically by overcoming frictional resistance.

The relation which exists between electrical and heat energy has been established by physicists, the value arrived at being called the *electrical equivalent of heat.* The value of the electrical equivalent of heat, as commonly used in the laboratory, is expressed as follows:

$$1 \text{ Btu} = 1055 \text{ watt-seconds.}$$
$$1 \text{ watt-second} = 1/1055 \text{ Btu.}$$

23. Determination of the Electrical Equivalent of Heat.—The electrical equivalent of heat may be determined in the laboratory by immersing an electrical resistance in water and measuring the number of watt-seconds required to raise the temperature of one pound of water one degree Fahrenheit. (See Fig. 7.) In this manner it has been found that one Btu is equivalent to 1055 watt-seconds. That is, *it would require 1055 sec for a current of one*

ampere flowing through a resistance of one ohm to raise the temperature of one pound of water one degree Fahrenheit.

In the following example, the electrical equivalent of heat was determined by immersing an electric lamp bulb in a metal container which was about half filled with water. When the current was turned on, the heat energy given off by the lamp was transferred to the water, causing a rise in temperature of the water.

Example 1.

During a determination of the electrical equivalent of heat the following data were taken: temperature of room, 66.2 deg fahr; weight of container, 1.33 lb; specific heat of container, 0.09; weight of water,

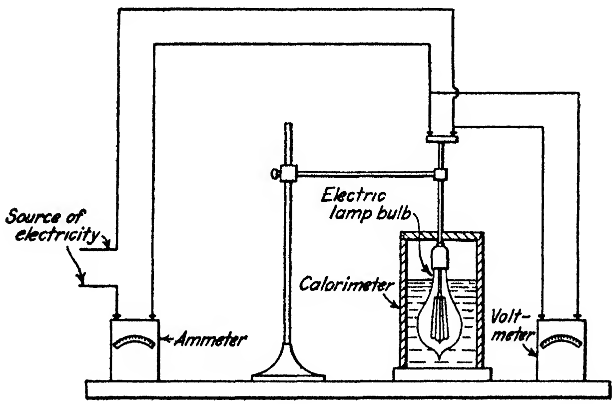


FIG. 7.—Apparatus for determining electrical equivalent of heat.

3.26 lb; initial temperature of water, 60.8 deg fahr; final temperature of water, 73.4 deg fahr; average ammeter reading, 0.40; average voltmeter reading, 110.0; duration of test, 1011 sec. Determine the value of the electrical equivalent of heat from these data.

Solution.

Heat absorbed by water and container = $[0.09 \times 1.33(73.4 - 60.8)] + [1 \times 3.26(73.4 - 60.8)] = 42.21$ Btu.

Total electrical energy supplied = $0.40 \times 110 \times 1011 = 44{,}500$ watt-seconds.

Hence 42.21 Btu = 44,500 watt-seconds.

Then 1 Btu = 44,500/42.21 = 1055 watt-seconds.

24. Relations between Heat, Electrical, and Mechanical Energy.—Since one horsepower is equal to 550 ft-lb per sec, or

33,000 ft-lb per min, and since one Btu of energy is equal to 778 ft-lb, it follows that one horsepower is also equal to 550/778 = 0.707 Btu per sec, or 33,000/778 = 42.41 Btu per min. As there are 60 min in one hour, the horsepower-hour is equal to 42.41 × 60 = 2545 Btu. The horsepower hour is also equal to 33,000 × 60 = 1,980,000 ft-lb.

The commercial unit of electrical energy is the kilowatt-hour. The kilowatt-hour is equal to 1000 watt-hours, or 1000 × 60 × 60 = 3,600,000 watt-seconds. But since 1055 watt-seconds is equal to one Btu, then 3,600,000 watt-seconds is equivalent to 3,600,000/1055 = 3414 Btu. Hence, we may state that one kilowatt-hour = 3414 Btu. That is, one kilowatt is a rate of 3414 Btu per hour.

The foregoing statements may be summarized as follows:

1 horsepower	=	33,000 ft-lb per min.
1 horsepower	=	42.41 Btu per min.
1 horsepower-hour	=	2545 Btu.
1 kilowatt	=	44,268 ft-lb per min.
1 kilowatt	=	56.9 Btu per min.
1 kilowatt-hour	=	3414 Btu.

25. Efficiency of Energy Changes.—The **efficiency** of an energy transfer process is the quotient obtained by dividing the amount of energy obtained from the process in the form of "output energy" by the energy put into the process in the form of "input energy," that is,

$$\text{Efficiency} = \frac{\text{Output energy}}{\text{Input energy}} \quad \ldots\ldots \quad (6)$$

In order to state efficiency on a percentage basis, it is necessary to have the output energy and the input energy in the same units, so that the units will cancel each other in the numerator and denominator of the efficiency ratio.

SUMMARY OF CHAPTER I

HEAT ENERGY is Energy of Motion. This definition is based on the assumption that matter consists of very small particles called molecules which are in a state of constant motion, heat being the kinetic energy due to this intermolecular activity.

HEAT FLOW can exist only where two substances are at different temperature levels, THERMAL EQUILIBRIUM being the condition where substances are at the same temperature level.

TEMPERATURE expresses how much hotter or colder a body is with respect to some other body. Temperature is a relative term and only tells which way we may expect heat energy to be transferred.

The MERCURY THERMOMETER consists of a fine glass tube in which mercury expands and contracts because of changes in temperature. The FIXED POINTS on a mercury thermometer are taken as the freezing and boiling points of pure water.

The CENTIGRADE THERMOMETER has 100 divisions or degrees between the two fixed points.

The FAHRENHEIT THERMOMETER has 180 divisions or degrees between the two fixed points. The zero degree mark on the Fahrenheit scale is 32 degrees below the freezing point. This fact should always be remembered in changing from one system to the other. The following equation may be used to transfer a temperature reading from Fahrenheit to Centigrade, or vice versa:

$$\frac{F - 32}{9} = \frac{C}{5}$$

where

F = degrees Fahrenheit,
C = degrees Centigrade.

The Calorie and Btu are quantity units of heat energy and consequently are work units.

A CALORIE is the quantity of heat necessary to raise the temperature of one gram of water one degree Centigrade.

A Btu is the quantity of heat necessary to raise the temperature of one pound of water one degree Fahrenheit.

The SPECIFIC HEAT of a substance is the amount of heat required to raise the temperature of a unit weight of the material one degree. It is a measure of the capacity of a substance to take up heat energy and may be expressed as Btu per lb per deg fahr, or Cal per gm per deg cent, the numerical value for the specific heat of any one material being the same in both the metric and English systems.

To find the heat required to CHANGE the temperature of a substance from t_1 to t_2 the following equation is given:

$$H = SW(t_2 - t_1)$$

The MECHANICAL EQUIVALENT OF HEAT is the name given to the number of foot-pounds of mechanical energy that are equal to one Btu. This can be determined only by experiment, and the commonly accepted value is 778 ft-lb = 1 Btu.

The ELECTRICAL EQUIVALENT OF HEAT is the name given to the number of watt-seconds of electrical energy that are equal to 1 Btu. This is also a constant that can be established only through

experimental means, and its accepted value is 1055 watt-seconds = 1 Btu.

The EFFICIENCY OF AN ENERGY TRANSFER PROCESS is equal to the ratio between the OUTPUT ENERGY and the INPUT ENERGY, so that:

$$\text{PERCENT EFFICIENCY} = \frac{\text{OUTPUT}}{\text{INPUT}}$$

REVIEW PROBLEMS ON CHAPTER I

1. Change 95 deg fahr to degrees Centigrade.

2. Change 40 deg cent to Fahrenheit.

3 Change 50 deg cent to Fahrenheit.

4. Change 240 deg fahr to Centigrade.

5. Change − 40 deg cent to Fahrenheit.

6. Change − 20 deg fahr to Centigrade.

7. Normal body temperature is 98 deg fahr. What would it be on the Centigrade scale?

8. Zinc melts at approximately 415 deg cent. What is its melting point on the Fahrenheit scale?

9. If oxygen boils at − 297 deg fahr, what is its boiling point on the Centigrade scale?

10. If carbon dioxide boils at − 79 deg cent, what is its boiling point on the Fahrenheit scale?

11. How many Btu are required to raise the temperature of 13 lb of water from 41 deg fahr to 177 deg fahr?

12. If 14,600 Btu were supplied to 103 lb of water, what temperature change would result?

13. It was found that 19.14 Btu were supplied in order to raise the temperature of a block of steel through 14 deg fahr. What was the weight of the steel block?

14. If 2.13 Btu of heat energy are required to raise the temperature of 1 lb of aluminum from 40 deg fahr to 50 deg fahr, what is the specific heat of the aluminum?

15. It is desired to raise the temperature of 2 lb of ethyl alcohol 20 deg fahr. How many Btu must be supplied?

16. What temperature change will result from supplying 67.68 Btu to 6 lb of brass? (Specific heat of brass = 0.094.)

17. How many Btu will it take to raise 250 lb of iron from 10 deg fahr to 45 deg fahr?

18. If the same quantities of heat were supplied to equal weights of copper and lead, which would undergo the greater temperature change? Give reason for your answer.

19. How many foot-pounds would be necessary to produce a temperature change of 67 deg fahr on 250 lb of lead? (Specific heat of lead is 0.0315.)

20. How many foot-pounds of mechanical energy would it take to raise the temperature of 1 ton of water from 42 deg fahr to 184 deg fahr?

21. A cast-iron flywheel is fitted with a prony brake equipped with cast-iron shoes. If the wheel and shoes weigh 100 lb, and 8.3 hp is being absorbed, how much would the rise in temperature be in 5 min if no heat were lost?

22. A 550-watt electric toaster should radiate how many Btu per minute if all the energy were radiated?

23. An incandescent lamp uses 50 watts of electricity, 88 percent of which is given off as heat. How many Btu of heat are thus given off per hour?

24. How many foot-pounds of work are there in 1 lb of coal containing 12,000 Btu?

25. How many horsepower-hours of work are in 1 ton of coal containing 12,500 Btu per lb?

26. How many kilowatt-hours in 1 ton of coal containing 13,200 Btu per lb?

27. Calculate the number of Btu in a horsepower-hour.

28. A certain heat engine has an efficiency of 11 percent. In burning 5 lb of coal, how much work can it do? (One pound of coal gives out 14,000 Btu.)

29. If the engine in problem 28 burns the 5 lb of coal in 1 hr, what horsepower is developed?

30. An engine is able to do 70 million ft-lb of work by burning 112 lb of coal. How many pounds of coal does it consume per horsepower-hour?

31. If mechanical energy is transformed into heat energy at the rate of 12 hp, how many Btu per hour will result?

32. How many pounds of water must be stored at a height of 100 ft above the point of usage to equal the amount of energy contained in 1 lb of coal yielding 13,800 Btu?

33. A power plant has an efficiency of 12 percent when run at its maximum capacity. It delivers 1800 kw. Find its coal consumption per day of 24 hr, if the Btu content of the coal per pound is 13,200.

34. A steam plant uses 1.5 lb of coal per horsepower per hour. Find the theoretical plant efficiency if each pound of coal contains 13,600 Btu.

35. A power plant has a coal consumption when run at full capacity of 25 tons per day of 24 hr. If its efficiency is 10 percent, how many horsepower does it develop? (Coal = 13,200 Btu per lb.)

36. If the average plant efficiency of the generating station of an electric illuminating company is 12 percent, and if the company pays

$3.00 per ton of 2000 lb for a coal which contains 12,400 Btu per lb, what does it cost the company for electricity per kilowatt-hour "generated"?

37. The flow of water from the tailrace of a mill is 1000 cu ft per min. If the water drops 12 ft to reach the water-wheel, what horsepower will the wheel deliver if its efficiency is 6 percent?

38. How many pounds of coal of 14,000 Btu per lb would a heat engine require per hour to generate the horsepower in problem 37, assuming an efficiency of 20 percent for the engine?

39. An apparatus has the capacity of absorbing 11 Btu per sq ft per min. How many square feet of surface must it have in order that it may absorb 10 hp?

40. An apparatus exposing 1000 sq ft of surface receives on the average, during a 10-hr day, 5 Btu per sq ft per min. If the apparatus transforms the energy received into mechanical energy with an efficiency of 2 percent, what average horsepower is developed during the 10 hr?

CHAPTER II

CALORIMETRY

26. Specific Heat of Water Not Constant.—Water, like all other substances, does not have the same specific heat at all temperatures; the specific heat of water varies with the temperature, being unity only for the temperatures of 55 and 158 deg fahr. This relation between the specific heat and temperature of water has been shown by the curve in Fig. 5. However, since the deviation from unity is small, no significant error results if the value for the specific heat is taken as unity over its entire temperature range. This is common practice and simplifies the calculations involved in calorimetry without introducing any serious error in most results.

27. Calorimetry.—*Calorimetry is the process of measuring quantities of heat.* The apparatus used to accomplish this result is known as a **calorimeter.** The name calorimeter is applied to a great variety of apparatus, so that the only thing the term designates is the use to which the apparatus is put. The calorimeters in use in elementary laboratories are usually very simple copper vessels protected from drafts, radiation, etc., by an outer vessel or jacket. Fuel calorimeters are frequently elaborate platinum-lined steel bombs, whereas steam calorimeters are sometimes little more than a steam pipe, with a pressure gage, valve, and exhaust chamber containing a thermometer.

28. Method of Mixtures.—Calorimetry in its simplest form is best illustrated by the **method of mixtures.** The method gets its name from the fact that two substances such as lead shot and water are mixed together in a calorimeter. These substances are at different, but known, temperatures before mixing. After mixing they are allowed to come to a common temperature, and this temperature is read. To illustrate this, let us suppose that a quantity of lead shot at 180 deg fahr is dropped into a calorimeter containing water which is at 70 deg fahr. When the lead shot is

mixed with the water, the shot loses a part of its heat to the water, thereby lowering the temperature of the lead and raising the temperature of the water. Presently a state of equilibrium is reached at which the temperature of the shot and the temperature of the water are the same, as, for example, 80 deg fahr. This final temperature depends upon the weight and the specific heat of each of the two mixed substances.

The assumption is made that no heat is lost to outside bodies, so that the amount of heat lost by the hot substance (the lead shot) is equal to the amount of heat gained by the cold substance (the water), or:

Heat gained by cold bodies = Heat lost by hot bodies, that is:

$$S_c \times W_c(t_f - t_c) = S_h \times W_h(t_h - t_f) \quad . \quad . \quad . \quad (7)$$

where the subscripts c and h refer to cold and hot bodies respectively.

t_c = original temperature of the cold body before mixing, deg fahr.

t_h = original temperature of the hot body before mixing, deg fahr.

t_f = final temperature of both bodies after equilibrium has been reached, deg fahr.

Example 1.

Assume that 2 lb of brass at 200 deg fahr are mixed with 6 lb of water at 70 deg fahr. The resulting temperature is 74 deg fahr. Determine the specific heat of the brass.

Solution.

Heat gained by the water = Heat lost by the brass,

or

$$S_c \times W_c(t_f - t_c) = S_h \times W_h(t_h - t_f)$$

$$1 \times 6(74 - 70) = S_h \times 2(200 - 74)$$

$$S_h = \frac{6(74 - 70)}{2(200 - 74)} = \frac{24}{252}$$

$$S_h = 0.0952 \text{ Btu per lb per deg fahr.}$$

Example 2.

A 5-lb weight of iron (specific heat = 0.115 Btu per lb per deg fahr) was placed in 15 lb of water at 80 deg fahr. If the resulting temperature was 85 deg fahr, what was the initial temperature of the iron weight?

Solution.

Heat gained by the water = Heat lost by iron weight,

or
$$
\begin{aligned}
S_c \times W_c(t_f - t_c) &= S_h \times W_h(t_h - t_f)\\
1 \times 15(85 - 80) &= 0.115 \times 5(t_h - 85)\\
(15 \times 5) &= 0.575(t_h - 85)\\
75 &= 0.575t_h - 48.875\\
75 + 48.875 &= 0.575t_h\\
123.875 &= 0.575t_h
\end{aligned}
$$

$$t_h = \frac{123.875}{0.575} = 215.4 \text{ deg fahr.}$$

Example 3.

What weight of copper at 240 deg fahr will be required to raise 60 lb of oil from 50 deg fahr to 70 deg fahr? (Specific heat of copper = 0.095 Btu per lb per deg fahr; specific heat of oil = 0.576 Btu per lb per deg fahr.)

Solution.

Heat gained by the oil = Heat lost by the copper,

or
$$
\begin{aligned}
S_c \times W_c(t_f - t_c) &= S_h \times W_h(t_h - t_f)\\
0.576 \times 60(70 - 50) &= 0.095 \times W_h\ (240 - 70)
\end{aligned}
$$

$$W_h = \frac{0.576 \times 60(70 - 50)}{0.095 \times (240-70)} = \frac{691.2}{16.15}$$

$$W_h = 42.8 \text{ lb of copper.}$$

Example 4.

Into a calorimeter containing 2.0 lb of water at 50 deg fahr, 1.2 lb of nickel at 212 deg fahr is dropped. The final temperature of the mixture becomes 59.7 deg fahr. The calorimeter weighes 0.5 lb and has a specific heat = 0.10. What is the specific heat of the nickel?

Solution.

Heat gained by water + Heat gained by calorimeter = Heat lost by nickel.

Heat gained by water = $1 \times 2(59.7 - 50) = 19.4$ Btu.

Heat gained by calorimeter = $0.10 \times 0.5(59.7 - 50) = 0.485$ Btu.

Heat lost by nickel = $S \times 1.2(212 - 59.7) = 182.76S$ Btu.

Therefore $19.4 + 0.485 = 182.76S$

$$S = \frac{19.4 + 0.485}{182.76} = \frac{19.885}{182.76} = 0.109 \text{ Btu per lb per deg fahr.}$$

29. Method of Total Heats.—A second method of calculation for calorimetry problems is often used. This method is based on the principle that the sum of the total heat contents of both the hot and cold bodies before mixing is equal to the sum of the total heat contents of both bodies after mixing. This may be more briefly stated by saying: *The sum of the total heats before mixing is equal to the sum of the total heats after mixing.* This statement is true only when no heat is lost to outside bodies by radiation or by any other means.

Before we speak of the total heat content of a body, however, we must choose some reference temperature at which the heat content of the body is assumed to be zero. In common practice this reference temperature has been arbitrarily chosen as 32 deg fahr, which means that if a body is at 32 deg fahr its heat content is 0 Btu. (The student should understand that this statement is in no sense of the word true, but is merely assumed as such for convenience. In fact, by following this method of reasoning, a body whose temperature is below 32 deg fahr would have a heat content of less than 0 Btu, which we know could not be true.)

The total heat above 32 deg fahr of any body = (its specific heat) × (its weight) × (its Fahrenheit temperature −32), or: Total heat above 32 deg fahr for a body

$$= S \times W(t - 32) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where

S = specific heat of the body, Btu per lb per deg fahr.
W = weight of the body, lb.
t = temperature of the body, deg fahr.

Thus, if an 18-lb piece of nickel is at 190 deg fahr, its total heat content above 32 deg fahr would be $= 0.110 \times 18(190 - 32) = 312.8$ Btu (assuming the specific heat of nickel as 0.110 Btu per lb per deg fahr). The total heat of a body above 32 deg fahr is often referred to by the term **sensible heat.**

Let us see how this method of total heats is applied to calorimetry problems by resolving **Example 1** under Art. 28.

Example 1.

Assume that 2 lb of brass at 200 deg fahr are mixed with 6 lb of water at 70 deg fahr. The resulting temperature is 74 deg fahr. Determine the specific heat of the brass.

Solution.

Total heat above 32 deg fahr for the water *before* mixing $= SW(t - 32) = 1 \times 6(70 - 32) = 228$ Btu.

Total heat above 32 deg fahr for the brass *before* mixing $= SW(t - 32) = S \times 2(200 - 32) = 336S$ Btu.

Total heat above 32 deg fahr for the water *after* mixing $= SW(t - 32) = 1 \times 6(74 - 32) = 252$ Btu.

Total heat above 32 deg fahr for the brass *after* mixing $= SW(t - 32) = S \times 2(74 - 32) = 84S$ Btu.

Sum of the total heats before mixing
= Sum of the total heats after mixing.

Therefore $228 + 336S = 252 + 84S$.

Hence $S = 24/252 = 0.0952$ Btu per lb per deg fahr.

It should be noticed at this point that we have obtained the same answer to the foregoing problem by this method of solution as we did by the method of mixtures. Although this latter method of solution is apparently a more cumbersome one, the authors suggest that the student master it completely as it is indispensable where steam is employed as one of the substances in the mixing process. This point will be more fully understood after the student has completed a study of the properties of steam as outlined in Chapter IV of this text.

30. Water Equivalent of a Calorimeter.—We have seen, from a study of the problems relating to Articles 28 and 29, that the calorimeter itself plays an important part in calorimetry calculations in that it absorbs a certain amount of heat during the calorimetry process.

If the water is allowed to remain in the calorimeter for a short period of time before the actual calorimetry process is started, the water and the calorimeter will come to a common temperature and the calorimeter thereafter will undergo practically the same temperature change as the water. Under these conditions the calorimeter absorbs an amount of heat, in Btu, equal to (weight of calorimeter) $\times$ (specific heat of calorimeter) $\times$ (temperature change of the water). Then the amount of heat that the calorimeter absorbs per degree change in temperature will be equal to (weight of calorimeter) $\times$ (specific heat of calorimeter). This product is known as the *water equivalent* of the calorimeter, in that it represents the weight of water that would absorb the same quantity of heat as the calorimeter itself absorbs during the process of calorimetry. It is the custom to add the water equivalent of

the calorimeter to the weight of water in the calorimeter and to multiply this sum by the temperature change of the water, thus including the thermal capacity of the calorimeter along with the water present. This calculation gives the amount of heat absorbed by both the water and the calorimeter without making separate calculations for each and adding them together afterwards.

The type of calorimeter usually employed in elementary laboratories is commonly made of nickel-plated sheet copper, and has a specific heat in the neighborhood of 0.10. The water equivalent of such a calorimeter would therefore be 0.10 × weight of calorimeter. In most calorimetry experiments it is customary to weigh the thermometer and stirrer with the calorimeter and treat them as a part of the calorimeter. If, however, extreme accuracy is desired, or if the calorimeter is constructed of a variety of materials of unknown specific heats, its water equivalent may be found by experiment.

Example 1.

Assume that 5.81 lb of water at 50.3 deg fahr is placed in a copper calorimeter that weighs 0.88 lb. A piece of aluminum that weighs 1.48 lb is dropped into the water. If the initial temperature of the aluminum was 212 deg fahr, and the final temperature of the mixture after stirring was 58.5 deg fahr, what was the specific heat of the aluminum? (Assume specific heat of copper = 0.10.)

Solution.

Water equivalent of calorimeter $= 0.10 \times 0.88 = 0.088$ lb.
Weight of water in calorimeter $= 5.810$ lb.
Equivalent weight of water $= 0.088 + 5.810 = 5.898$ lb.
Total heat of water above 32 deg fahr *before* mixing:

$$1 \times 5.898(50.3 - 32) = 107.9 \text{ Btu.}$$

Total heat of aluminum above 32 deg fahr *before* mixing:

$$S \times 1.48(212 - 32) = 266.4S \text{ Btu.}$$

Total heat of water above 32 deg fahr *after* mixing:

$$1 \times 5.898(58.5 - 32) = 156.3 \text{ Btu.}$$

Total heat of aluminum above 32 deg fahr *after* mixing:

$$S \times 1.48(58.5 - 32) = 39.2S \text{ Btu.}$$

Sum of the total heats before mixing
= Sum of the total heats after mixing.

$$107.9 + 266.4S = 156.3 + 39.2S$$

$$227.2S = 48.4$$

$$S = \frac{48.4}{227.2} = 0.214 \text{ Btu per lb per deg fahr.}$$

CALORIMETRY OF FUELS

31. Fuels.—Any substance that may be oxidized or burned and thereby made to produce heat in commercial quantities is called a fuel. Commonly, fuels are made up either of pure carbon, or of compounds of carbon formed with hydrogen, nitrogen, oxygen, sulphur, etc. The most common solid fuel is coal. The common liquid fuels are petroleum products. Gaseous fuels usually include natural gas, evaporated petroleum products, and coal distillates.

32. Heat Produced by the Combustion of a Fuel.—The purpose of burning any fuel is to produce heat. The amount of heat produced by the *complete burning of one pound* of a solid fuel is known as its **heating value.** To measure the heat produced by the burning of one pound of a solid fuel, it is necessary to burn a small sample of the fuel under conditions that will produce complete combustion, thereby enabling the investigator to measure all the heat giving up during the burning.

Thus, if the heat produced by the burning of a given quantity of coal is to be measured, the coal is burned in a chamber that is completely surrounded by water. The apparatus used for this determination is known as a **bomb calorimeter,** the essential parts of which are illustrated in Fig. 8. About one gram of finely powdered coal is placed in the platinum crucible. The crucible is placed in the thick-walled bomb, which is air-tight, and is connected with an oxygen tank under a pressure usually in the neighhood of 250 lb per sq in. The bomb is surrounded by a copper calorimeter which contains about 5 lb of water. Radiation of heat from the calorimeter is minimized by means of an insulating jacket. A thermometer projects into the water, and the water is constantly stirred by a suitable device.

The coal sample in the crucible is ignited electrically by a coil of platinum wire which receives its current from outside the bomb. Upon the passage of current through the platinum wire, the wire becomes red-hot, causing the oxygen to unite chemically with the coal. The coal burns, causing the temperature of the water in the calorimeter to rise. The number of Btu given off by the coal in burning = (weight of water in calorimeter + water equivalent of calorimeter) $\times$ (rise in temperature of water).

The foregoing method for determining the heating value of solid fuels can be applied to liquid fuels as well. Heavy liquid fuels, such as crude oil, may be weighed directly in the crucible; but light liquid fuels that evaporate readily are often placed in specially prepared glass containers which are broken just before the cover is put on the bomb.

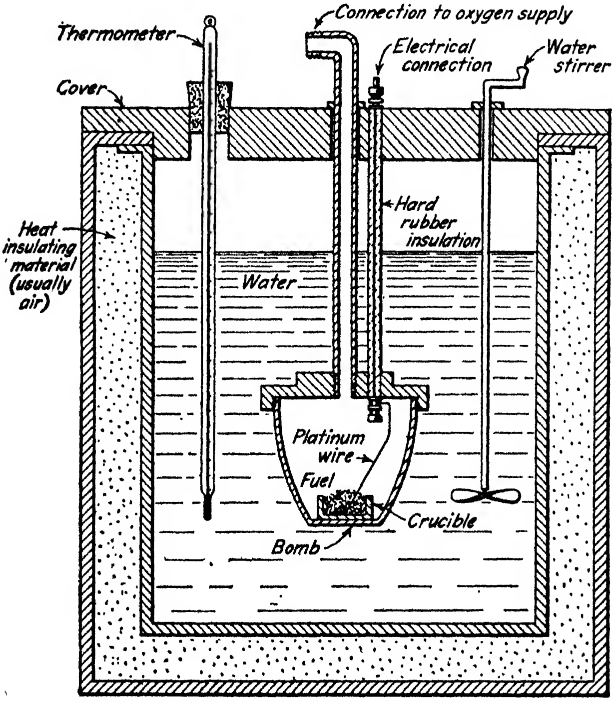


FIG. 8.—Sectional view of a bomb calorimeter.

Example 1.

The following data were taken during an experiment to determine the heating value of a given sample of bituminous coal:

Weight of coal burned, grams	1.00
Weight of water in calorimeter, lb	5.20
Water equivalent of calorimeter, lb	0.50
Initial temperature of water, deg fahr	65.0
Final temperature of water, deg fahr	71.2

Determine the heating value of this coal in Btu per lb.

Solution.

Heat given up by the burning of 1 gram of coal

= Heat absorbed by water.

Btu per gram of coal = $5.7(71.2 - 65)$ = 35.3 Btu.

Btu per lb of coal = 35.3×453 = 16,000 Btu.*

* Note 453 grams = 1 lb.

33. Calorimetry of Gaseous Fuels.—Fig. 9 is a diagram showing the flow of water and gas in a piece of apparatus known as a **Junker calorimeter.** This apparatus is used to determine the amount of heat energy in Btu that is produced by the combustion of a given quantity of any combustible gas. It is customary commercial practice to specify the heating value of a gas by stating the number of Btu per cubic foot that the gas gives off when completely burned. For example, if the heat produced by the burning of a cubic foot of illuminating gas is to be measured, the gas is burned in a Bunsen burner which is placed in the central portion of the Junker calorimeter. The hot gases resulting from the combustion are surrounded by running water during their entire journey through the calorimeter. Thus the

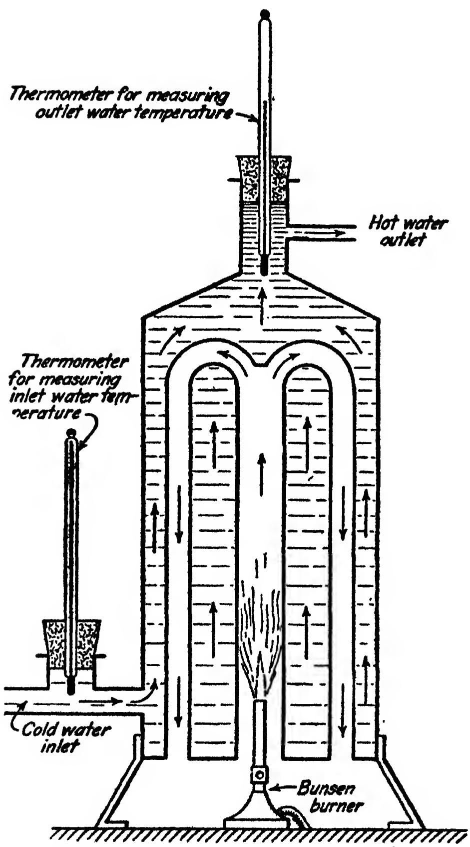


Fig. 9.—Sectional view of a Junker calorimeter.

heat liberated by the burning gas causes a rise in temperature of the water flowing through the calorimeter. If certain corrections and refinements of method are ignored, the heat units liberated by a measured quantity of gas, as supplied, can then be determined approximately by calculating the amount of heat absorbed by the water flowing through the calorimeter. The Btu absorbed by the water during a given test will be equal to the weight of water used, times the temperature change that the water undergoes. This result divided by the number of cubic feet of gas used during the test will give the heating value of the gas in Btu per cubic foot.

Example 1.

The following data were taken during a test to determine the heating value of a certain illuminating gas:

Total amount of water passed through the Junker calorimeter, lb = 42.5.

Temperature of the inlet water to calorimeter, deg fahr = 62.0.

Temperature of outlet water from calorimeter, deg fahr = 85.0.

Total number of cubic feet of illuminating gas used during test = 1.75.

Determine the heating value of the gas in Btu per cubic foot.

Solution.

Heat absorbed by water = Heat liberated by illuminating gas.

Heat absorbed by water = 42.5(85 − 62) = 977.5 Btu.

$$\text{Heating value of gas} = \frac{977.5}{1.75} = 559 \text{ Btu per cu ft.}$$

SUMMARY OF CHAPTER II

It is common practice to use UNITY as the value for the SPECIFIC HEAT OF WATER for all calorimetry problems.

CALORIMETERS are instruments with which QUANTITY OF HEAT ENERGY is measured. Calorimetry is the name given to the process of measuring quantities of heat. In calorimetry, HEAT EQUATIONS are written based upon the assumption that no heat is lost during the calorimetry period. Thus:

(1) Heat gained by cold bodies = Heat lost by hot bodies.

(2) Total heat of all bodies before mixing = Total heat of all bodies after mixing.

The term total heat refers to the total heat of a body above 32 deg fahr.

This is commonly called the **SENSIBLE HEAT** of the body and may be expressed by the following equation:

$$\text{Total heat above 32 deg fahr} = SW(t - 32).$$

The **WATER EQUIVALENT** of a calorimeter is the weight of water that will absorb the same quantity of heat as the calorimeter itself does during the calorimetry process. The equivalent weight of water, or water equivalent, is equal to (specific heat of calorimeter) × (weight of calorimeter).

A **FUEL** is any substance that will burn and produce heat in commercial quantities. There are three different forms of fuel: solid, liquid, and gaseous.

The **HEATING VALUE** of a solid or liquid fuel is the number of Btu that are given off as heat when one pound of the fuel is completely burned. The **HEATING VALUE** of a gaseous fuel is the number of Btu given off by the complete burning of one cubic foot of the gas.

A **BOMB CALORIMETER** is especially designed to determine the heating value of solid or liquid fuels. The fuel to be tested is burned in a chamber which is completely surrounded by water so that the heat produced by combustion is absorbed by the water. The rise in temperature of the water multiplied by the weight of water (including the water equivalent of the colorimeter) is equal to the heating value of the burned sample of coal.

The **JUNKER CALORIMETER** is an instrument commonly used to determine the heating value of gaseous fuels. A measured quantity of gas is burned in the calorimeter, producing a change in temperature of the water flowing through it. The weight of water used, times the temperature change of the water, equals the Btu given off by the burning of the gas.

REVIEW PROBLEMS ON CHAPTER II

1. Explain why the numerical value for the specific heat of a material is the same for the English system of weights and temperatures as it is for the metric system of weights and temperatures.

2. An iron ball weighing 6 lb is heated in boiling water at 212 deg fahr, and then dropped into 4 lb of water at 35 deg fahr. Temperature of water rises to 60 deg fahr. What is the specific heat of the iron?

3. Ten pounds of water at 180 deg fahr was poured into a copper beaker weighing 2 lb and containing 8 lb of water at 50 deg fahr. What was the resulting temperature? (Specific heat of copper = 0.093 Btu per lb per deg fahr.)

4. Two pounds of aluminum at 50 deg fahr, 4 lb of copper at 100 deg fahr, and 10 lb of cast iron at 200 deg fahr were all simultaneously plunged

into 3 cu ft of water at 40 deg fahr. What was the final temperature of the mixture?

5. A steam boiler containing 2 tons of water at a temperature of 200 deg fahr is supplied with water at 60 deg fahr from a feed-pump delivering 20 gal per min. If the pump is kept running for 10 min, what will be the resulting temperature of the water in the boiler?

6. A number of brass condenser tubes weighing 540 lb were at a temperature of 58 deg fahr before the condenser was at work; afterward, when in use, the temperature of the condenser tubes became 110 deg fahr. How many Btu did they absorb?

7. What weight of water at 190 deg fahr would be required to produce the results obtained in problem 6?

8. A cast-iron plate weighing 120 lb is immersed in 240 lb of water at 50 deg fahr. If the initial temperature of the plate was 150 deg fahr, what was the final temperature?

9. It is desired to determine the specific heat of a piece of fire-brick weighing 2.83 lb. In order to accomplish this it was first heated in an oven until it reached a temperature of 1950 deg fahr, and then it was dropped into a calorimeter containing 19.8 lb of water at 40.6 deg fahr. The resulting temperature of the water was 100.8 deg fahr. What was the specific heat of the fire-brick? (Water equivalent of the calorimeter = 0.4 lb.)

10. One gram of coal was tested in a bomb calorimeter whose water equivalent was 0.98 lb. The water contained in the calorimeter weighed 3 lb. The initial and final temperatures of the water were 54.0 deg fahr and 60.9 deg fahr. What was the heating value of the coal in Btu per pound?

11. One gram of gasoline is burned in the bomb calorimeter of problem 10. The 3 lb of water in the calorimeter undergoes a temperature change from 50 deg fahr to 64.4 deg fahr. What was the heating value of the gasoline in Btu per pound?

12. The guaranteed heating value of the city gas in Rochester, N. Y., is 537 Btu per cu ft. The following Junker calorimeter test was conducted to verify this statement.

Number of cubic feet of gas burned	= 1.37
Weight of water passing through calorimeter, pounds	= 18.45
Inlet temperature of water, deg fahr	= 52.3
Outlet temperature of water, deg fahr	= 92.4

Did the actual heating value of the gas come up to the guaranteed heating value?

13. How many cubic feet of dry air at 32 deg fahr will 1 lb of coal containing 14,000 Btu warm to 72 deg fahr? (Specific heat of dry air = 0.237; 1 cu ft of air weighs 0.0807 lb)

14. An air-cooled gasoline engine has an efficiency of 20 percent, that is, 80 percent of the energy in the fuel is either carried off by the exhaust gases or radiated from the engine. This engine burns 24 lb of gasoline per hour, containing 19,500 Btu per lb, and for every pound of fuel burned 19 lb of air is carried through the cylinders. If the air is taken in at 60 deg fahr, and exhausted at 780 deg fahr, how many Btu per hour pass out through the exhaust? How much is left to be radiated per hour if the combustion is complete?

15. If in the engine referred to in problem 14, 60 percent of the heat energy in the fuel had been radiated from the engine, how many pounds of air would have been heated from 60 deg fahr to 180 deg fahr per hour?

CHAPTER III

EXPANSION OF SOLIDS, LIQUIDS, AND GASES

34. Expansion of Solids.—It is a matter of common experience that, in general, when bodies are heated they expand—that is, they undergo changes in dimension. Trolley and telegraph wires sag noticeably more in summer than in winter. In many forms of construction, allowance must be made for expansion and contraction of materials due to changes in temperature. For example, a concrete roadbed is laid in slabs with soft tar joints at intervals. If this were not done, the concrete would crack when it cools and contracts in the winter.

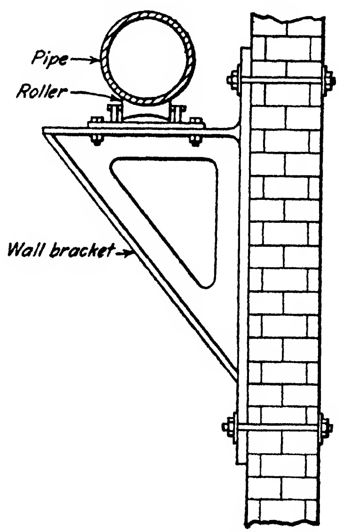


FIG. 10.—Wall bracket which allows for linear expansion of steam pipe.

One of the important problems in the installation of any steam pipe is to make proper provision for expansion and contraction of the pipe due to changes in temperature. In this case an allowance of $\frac{1}{2}$ in. per 100 ft of pipe is the usual amount that must be provided for thermal expansion. Fig. 10 represents a wall bracket commonly used for supporting steam pipes. It is so arranged that lineal expansion of the pipe may take place without damage to the supporting bracket or to the pipe.

Fig. 11 represents a railroad car wheel having a shrunk-on steel tire. This tire is originally machined to a slightly smaller diameter than the diameter of the wheel. When the tire is heated, it expands enough to allow it to be slipped over the wheel proper,

and upon cooling it binds tightly in place. If the rolling surface of such a tire becomes injured from service, it is a simple matter

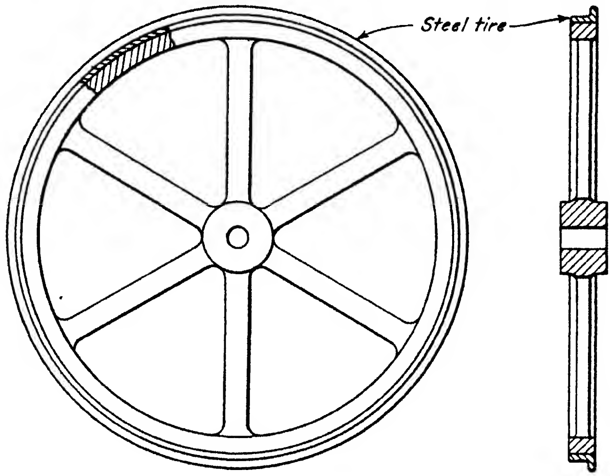


FIG. 11.—Train wheel having shrunk-on steel tire.

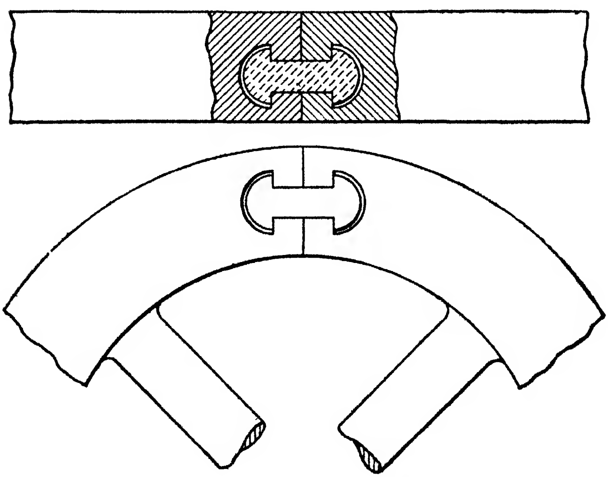


FIG. 12.—Diagram showing shrunk-link-joint used for holding segments of cast-iron flywheel together.

to " sweat " off the old tire and " shrink " on a new one. This same principle is employed to equip modern automobile fly-

wheels with replaceable starting gears. The starting gear consists of a circular band of steel in which the gear teeth are cut. This ring gear is machined to a smaller diameter than the outside diameter of the flywheel, and is " shrink-fitted " to the flywheel. Thus if the gear teeth on the flywheel are damaged, the gear ring may be replaced without replacing the whole flywheel.

In the construction of large flywheels for steam engines it is often necessary to cast the wheel in parts or segments. These segments may be held together in the manner shown in Fig. 12. The two segments are held together by a link, which is heated until it expands to a length which will allow it to be fitted into the space provided for it as shown in Fig. 12. Upon cooling, this link contracts, pulling the two segments of the flywheel together.

35. Expansion of Different Materials.—A piece of steel and a piece of brass of exactly the same length at room temperature are selected and riveted together as shown in Fig. 13*a*. This compound strip is clamped at one end as shown. If it is heated to a temperature higher than that of the room, the strip will warp, as shown in Fig. 13*b*, since at normal temperatures brass expands more than steel for any given temperature change. The construction of electric thermostats and dial thermometers is based on this principle.

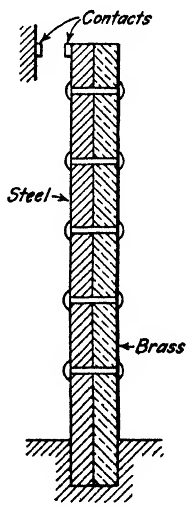


FIG. 13*a*. Thermostat, cold.

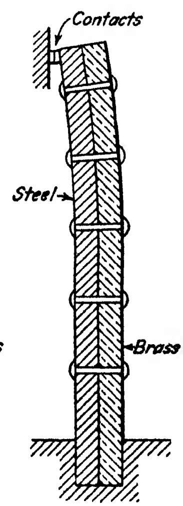


FIG. 13*b*. Thermostat, heated.

Repetition of this experiment with many different materials would show that no two materials expand exactly the same amount when subjected to identical temperature changes. The amount of expansion varies with each substance, and, furthermore, will vary for any one substance if the texture of the substance is not homogeneous.

The linear amount that a unit length of a material expands as the

result of a rise in temperature of one degree is expressed by a number called the **coefficient of linear expansion.** If the coefficient of linear expansion of a material is known, it is a simple matter to calculate the total change in dimension that will occur for any given temperature change. Table II gives the coefficient of linear expansion for a few of the common engineering materials.

The coefficient of linear expansion may be expressed more briefly in the form of an equation:

$$\text{Coefficient of linear expansion} = \frac{\text{Increase in length}}{(\text{Original length}) \times (\text{Rise in temperature})}. \quad . \quad . \quad (9)$$

The value of the coefficient of linear expansion is usually determined for the range of temperatures from 32 deg fahr to 212 deg fahr, and the average value taken.

It is important to notice that the unit of length appears in both the numerator and denominator of the foregoing equation, and therefore does not affect the numerical value of the coefficient. The unit of temperature, however, appears only in the denominator, and therefore a different numerical value of the coefficient must be used with Centigrade temperatures from that used with Fahrenheit temperatures. The values as tabulated in Table II are to be used with Fahrenheit temperatures; however, the corresponding Centigrade coefficient may be obtained by multiplying the Fahrenheit coefficient by $\frac{9}{5}$.

Example 1.

What change in length results when an 80-ft steam pipe is heated from a temperature of 70 deg fahr to a temperature of 350 deg fahr? The coefficient of linear expansion of iron = 0.0000065 on the Fahrenheit scale.

Solution.

$$0.0000065 = \frac{\text{Change in length}}{80 \times (350 - 70)}$$

Thus

$$\begin{aligned} \text{Change in length} &= 0.0000065 \times 80(350 - 70) \\ &= 0.1456 \text{ ft.} \\ &= 0.1456 \times 12 = 1.747 \text{ in.} \end{aligned}$$

Table II

COEFFICIENT OF EXPANSION OF VARIOUS MATERIALS

(Inches per inch per deg fahr)

Substance	Coeff.	Substance	Coeff.
Solids (linear)		*Liquids (cubical)*	
Aluminum	0.0000127	Alcohol (ethyl)	0.000583
Antimony	0.0000066	Alcohol (methyl)	0.000754
Brass (cast)	0.0000103	Benzine	0.000649
Brass (wire)	0.0000106	Ether	0.000836
Bismuth	0.0000088	Glycerin	0.000279
Carbon (coke)	0.0000030	Mercury	0.000100
Carbon (graphite)	0.0000043	Olive oil	0.000374
Copper	0.0000092	Petroleum	0.000495
German silver	0.0000101	Turpentine	0.000521
Glass (crown)	0.0000049	Water	0.000112
Glass (flint)	0.0000043		
Ice	0.0000281		
Iron (annealed)	0.0000061		
Iron (cast)	0.0000058		
Iron (wrought)	0.0000065		
Lead	0.0000160		
Masonry	0.0000025		
Nickel	0.0000055		
Paraffin	0.0000580		
Porcelain	0.0000020		
Quartz	0.0000001		
Silver	0.0000105		
Solder	0.0000126		
Steel	0.0000065		
Sulphur	0.0000352		
Tin	0.0000127		
Wood, parallel to fiber:			
Oak	0.0000027		
Pine	0.0000029		
Wood, across fiber:			
Oak	0.0000299		
Pine	0.0000018		
Zinc	0.0000160		

The corresponding Centigrade coefficients may be obtained by multiplying the Fahrenheit values given in the above table by $\frac{9}{5}$.

36. Coefficient of Expansion of an Area.—*The coefficient of expansion of an area may be defined as the increase in area which*

results when a surface of unit area undergoes a temperature change of one degree.

Let us consider a square plate such as shown in Fig. 14 which is of one material having the same texture throughout, and which has sides or edges of unit length. If this plate is heated, the final length of each edge becomes $(1 + at)$; where a is the coefficient of linear expansion of the material and t the temperature change. From this we may state:

$$\text{Final area of the plate} = (1 + at)(1 + at) = 1 + 2at + a^2t^2$$

However, since a itself is very small, the a^2t^2 term in the above expression may be disregarded as representing a quantity too small to be of significance. Thus, we may state the following approximation:

$$\begin{aligned} \text{Final area of the plate} &= 1 + 2at \\ \text{Then the increase in area} &= (1 + 2at) - 1 = 2at \end{aligned}$$

Hence, for practical purposes the coefficient of areal expansion may be taken as twice the value of the coefficient of linear expansion. The value of the coefficient of areal expansion may also be stated in equational form as follows:

The coefficient of areal expansion of any substance =

$$\frac{\text{Increase in area}}{(\text{Original area}) \times (\text{Rise in temperature})}. \quad . \quad . \quad (10)$$

Example 1.

A piece of sheet tin is 35 ft long and 20 ft wide. If it undergoes a temperature change of 50 deg fahr, what will be the increase in area of the tin in square inches? (Coefficient of linear expansion of tin = 0.0000127 on the Fahrenheit scale.)

Solution.

Areal expansion coefficient = $2 \times 0.0000127 = 0.0000254$.

Substituting in the foregoing equation, we have:

$$0.0000254 = \frac{\text{Change in area}}{(35 \times 20) \times 50}$$

$$\begin{aligned} \text{Change in area} &= 0.0000254 \times 35 \times 20 \times 50 = 0.889 \text{ sq ft} \\ &= 0.0889 \times 144 = 128 \text{ sq in.*} \end{aligned}$$

* Note: 144 sq in. = 1 sq ft.

This area of 128 sq in. must be taken care of by a buckling of the tin.

37. Coefficient of Cubical Expansion.—*The coefficient of expansion of a volume may be defined as the increase in volume which results when a unit volume undergoes a temperature change of one degree.*

Let us consider a cubical block of homogeneous material having sides of unit length, such as shown in Fig. 15. Now, using the symbols as before:

$$\begin{aligned}\text{Final length of each edge} &= (1 + at)\\ \text{Final volume of the cube} &= (1 + at)(1 + at)(1 + at)\\ &= 1 + 3at + 3a^2t^2 + a^3t^3\end{aligned}$$

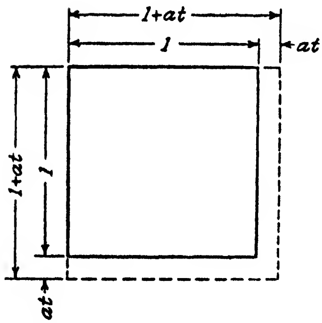


FIG. 14.—Expansion of a unit area.

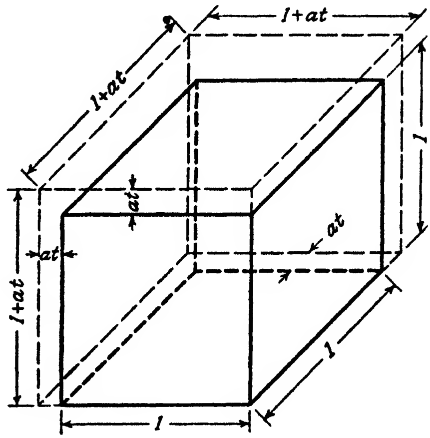


FIG. 15.—Expansion of a unit volume.

Neglecting the terms containing the square and cube of *a*, as representing values too small to be significant, we have:

Final volume of the cube $= (1 + 3at)$.

Therefore, the change in volume of the cube $= (1 + 3at) - 1 = 3at$.

Hence, the coefficient of cubical expansion for a given substance may be said to equal three times the value of the coefficient of linear expansion for that substance.

The coefficient of cubical expansion of any substance =

$$\frac{\text{Increase in volume}}{(\text{Original volume}) \times (\text{Rise in temperature})} \quad . \quad . \quad . \quad (11)$$

Example 1.

A block of wrought iron is 30 in. long, 20 in. wide, and 4 in. deep. What change in volume will result when the temperature is raised from 50 deg fahr to 100 deg fahr?

Solution.

From Table II, the linear coefficient of expansion for wrought iron = 0.0000061. Then, the coefficient of cubical expansion = 3 × 0.0000061 = 0.0000183.

Thus, substituting in the foregoing equation, we have:

$$0.0000183 = \frac{\text{Change in volume}}{(30 \times 20 \times 4)(100 - 50)}$$

$$\begin{aligned}\text{Change in volume} &= 0.0000183(30 \times 20 \times 4)(100 - 50)\\ &= 2.196 \text{ cu in.}\end{aligned}$$

38. Expansion of Liquids.—Cubical expansion, as previously defined, takes place in liquids. However, when a vessel containing a liquid is heated, both vessel and liquid expand; thus, the observed change in volume of the liquid is the difference between the actual change in volume of the liquid and the change in volume of the containing vessel. If the rate of cubical expansion of the vessel and liquid happened to be the same, no change in volume of the liquid would be observed. However, if the cubical expansion of the liquid is greater than that of the vessel, we would observe what is known as the *apparent cubical expansion of the liquid*; and, conversely, if the rate of expansion of the vessel were greater than that of the liquid, we would observe an apparent contraction of the liquid upon application of heat.

By measuring the apparent change in volume of the liquid in the vessel, giving it a minus sign if it is contraction, and dividing by the original volume multiplied by the rise in temperature, the numerical value for the *apparent* coefficient of cubical expansion is obtained.

The algebraic sum of the apparent coefficient of cubical expansion of the liquid and the coefficient of cubical expansion of the vessel gives the *absolute* coefficient of cubical expansion of the liquid.

The apparent coefficient of cubical expansion of a liquid in a vessel =

$$\frac{\text{Apparent change in volume of the liquid}}{(\text{Original volume of the liquid}) \times (\text{Rise in temperature})}. \quad (12)$$

Absolute coefficient of cubical expansion of the liquid

$$= \begin{cases} \text{Coefficient of cubical expansion of the vessel} \pm \text{Apparent} \\ \text{coefficient of cubical expansion of the liquid.} \end{cases}$$

The plus sign is used if the liquid apparently expands when heated; the minus sign, if the liquid apparently contracts in the vessel when heated.

Example 1.

A full crown glass vessel contains 400 cc of mercury at 0 deg cent. How much will it hold at 100 deg cent?

Solution.

$$\text{The apparent coefficient} = \frac{9}{5} \times 0.000100 - \left(3 \times \frac{9}{5} \times 0.0000049\right)$$

$$= 0.000154$$

The apparent increase in volume, or the overflow mercury

$$= (0.000154 \times 400 \times (100 - 0) = 6.16 \text{ cc}$$

Hence, there will remain in the vessel,

$$400 - 6.16 = 393.84 \text{ cc.}$$

39. Expansion of Water.—Water, like all other substances, increases in volume when heated, except for the temperature range from 32 deg fahr to 39 deg fahr, where it actually contracts when heated. Thus, if a given weight of water, say one pound at a temperature of 32 deg fahr, is heated, its volume will decrease until a temperature of 39 deg fahr is reached, after which expansion sets in. The maximum density (weight per unit volume) for water would therefore be at a temperature of 39 deg fahr.

This property is best demonstrated by the use of an apparatus such as shown in Fig. 16. The tank around the middle of this glass vessel is filled with an ice and salt solution. When the water in the middle of the inner vessel cools, it becomes denser and drops to the bottom, while the water above the middle will not be

disturbed. Thus, the upper thermometer will show a practically stationary temperature, and the lower thermometer a falling temperature, until all the lower half of the vessel is filled with water at 39 deg fahr; after this point has been reached, the temperature of the water in the upper half of the vessel begins to drop until 32 deg fahr is reached and freezing begins at the top, with the lower thermometer still indicating 39 deg fahr. The water at 39 deg fahr is more dense than water at any other temperature since it collects at the bottom of the vessel at this temperature.

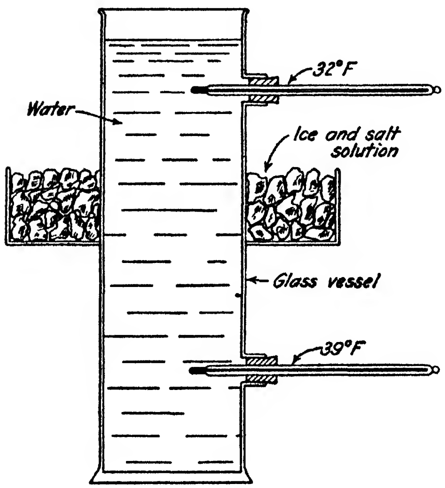


FIG. 16.—Determination of the maximum density of water.

When an open pond or lake cools in the winter, the water at the top cools first, becomes heavier, and sinks to the bottom, forcing the warmer and lighter water to the top. As this warmer water cools, it becomes heavier and sinks to the bottom, replacing the water there. This process continues until the water reaches a temperature of 39 deg fahr, after which it remains at the bottom, as it did in the foregoing experiment. The surface water then cools to 32 deg fahr and freezes, the water beneath the ice remaining at 39 deg fahr except for that in close contact with the ice.

EXPANSION OF GASES

40. Gases and Vapors.—A gas is a fluid which has no definite shape or volume, but expands to take the shape and dimensions of any vessel in which it is contained. The study of gases in this chapter will deal with so-called *perfect or permanent* gases, and not with vapors.

The distinction between a perfect gas and a vapor is one of degree. In the early study of gases, scientists called the gases

which they could not change into liquids by lowering their temperature, *permanent gases,* as for example, oxygen, hydrogen, nitrogen, etc. Such gases as steam and ammonia, however, were termed *vapors* since they could be readily changed into a liquid by cooling. Later investigations have shown that all gases may be changed into liquids when they are cooled to a sufficiently low temperature. The temperature at which a few of the so-called permanent gases liquefy are as follows:

Air	−312 deg fahr.
Oxygen	−296 deg fahr.
Hydrogen	−422 deg fahr.
Nitrogen	−316 deg fahr.

Gases at or near their liquefaction temperatures are known as vapors; and the general gas laws as set forth in this chapter do not even approximately apply to vapors.

41. Condition of a Gas.—The condition of a gas is specified when the following facts are known: (1) chemical composition, (2) weight, (3) volume, (4) pressure, (5) temperature. A study of gases may well begin with a discussion of item (4), pressure.

42. Pressure.— *Unit pressure is defined as force per unit area,* and is most commonly expressed in pounds per square inch, grams per square centimeter, etc. Thus, in the English system of measurement, unit pressure is equal to the total force in pounds divided by the area in square inches over which the total force is distributed.

$$\text{Unit pressure} = \frac{\text{Force}}{\text{Area}}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

For example, if a total force of 1000 lb is distributed over an area of 10 sq in. the unit pressure acting upon the area is $1000/10 = 100$ lb per sq in.

If a cubical tank one foot by one foot by one foot is filled with water, it will be found to hold approximately 62.5 lb. Thus the total weight on the *bottom* of the tank is 62.5 lb. This weight is distributed over an area of one square foot, or 144 sq in.; hence the pressure acting on one square inch of the bottom is $62.5/144 = 0.433$ lb. From this it is evident that a column of water one square inch in cross-section and one foot high produces a pressure

of 0.433 lb per sq in. Therefore we see that pressure may be measured in terms of the height of a column of water.

If the foregoing experiment were conducted with mercury instead of water, it would be found that a column of mercury one square inch in cross-section and one foot high produces a pressure of 5.892 lb per sq in. If the mercury level in the tank were only one inch high, a unit pressure of only 5.892/12 = 0.491 lb per sq in. would result. Thus:

One-foot head of water produces a pressure of
0.433 lb per sq in.
One-inch head of mercury produces a pressure of
0.491 lb per sq in.

43. Atmospheric Pressure.—*Atmospheric pressure is the downward force exerted on the earth's surface by the weight of air enshroud-*

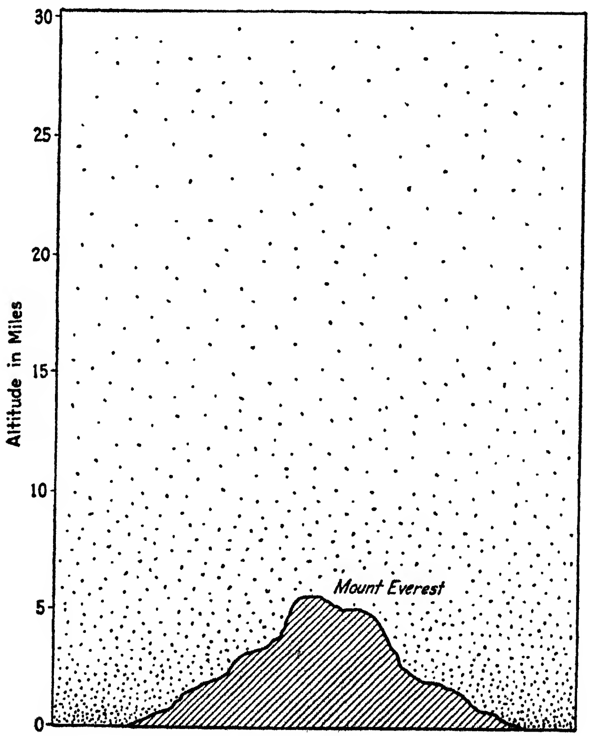


Fig. 17.—Diagram showing decrease in density of atmosphere with increase in elevation.

ing the earth. This layer or stratum of air extends upward from the surface of the earth for a distance of more than 50 miles. Thus the pressure on one square inch of the earth's surface is caused by the weight of a column of air one square inch in cross-section and 50 miles high. The weight of such an air column is approximately 14.7 lb at sea level; hence the unit atmospheric pressure is in the neighborhood of 14.7 lb per sq in. If the atmospheric pressure is measured at a point above sea level, as on a mountain, it will be less than 14.7 lb per sq in., since the height of air above that point is less. Fig. 17 is intended to suggest how atmospheric pressure decreases as the altitude above sea level is increased. The air at sea level is more dense than on the mountain top; accordingly, the decrease in pressure per foot of altitude is not uniform, but is maximum at sea level. Conditions 100 miles or above the earth's surface are still subjects of conjecture, since they have not been experimentally explored.

The instrument most commonly used to measure atmospheric pressure is the **mercury barometer.** A simple form of mercury barometer may be constructed as follows: Select a glass tube of fine bore that is about 3 ft long, and sealed at one end. Completely fill it with mercury. Next place a finger over the open end to prevent the mercury from spilling, and quickly immerse the open end of the tube into a cup of mercury, as shown in Fig. 18. When the finger is removed, the mercury will sink in the tube until it stands at a certain distance above the surface of the mercury in the cup; this distance is dependent upon the atmospheric pressure acting on the mercury surface in the cup. Thus we see that the mercury column is supported by the atmospheric pressure bearing downward on the surface of mercury outside of the tube.

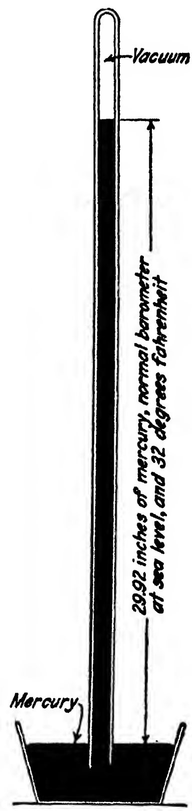


FIG. 18. — Simple barometer.

We have already found that a column of mercury one inch high is equivalent to a pressure of 0.491 lb per sq in.; thus if the

mercury column stands 30 in. high in the barometer tube the atmospheric pressure = 30 × 0.491 = 14.73 lb per sq in.

At sea level, when the temperature is 32 deg fahr, the mean atmospheric pressure tests out to be 14.7 lb per sq in. Scientists have arbitrarily selected this condition of pressure and temperature to represent so-called **standard conditions.**

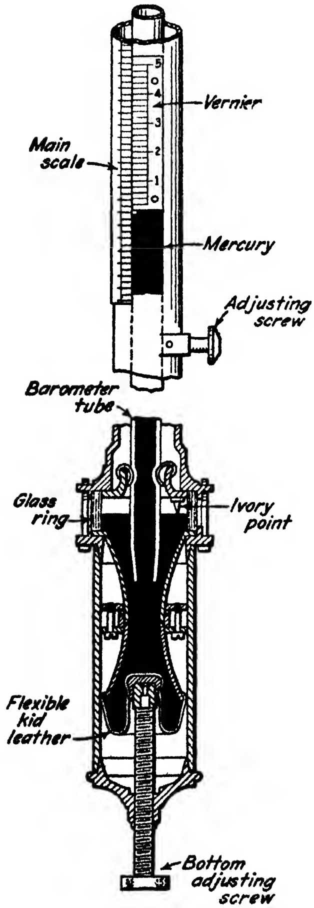


Fig. 19—Commercial barometer. (U. S. Weather Bureau Type.)

The commercial or standard type of mercury barometer is shown in Fig. 19. It consists of a long glass tube sealed at the top and enclosed in a brass tube which has a vernier scale at the top. Above the mercury column is a vacuum. The lower end of the glass tube dips into a mercury bath contained in a glass cup which has a leather bottom. This leather bottom rests on a disk which may be moved up and down by means of an adjusting screw. This adjusting screw should be regulated until the mercury in the cup just touches a fixed ivory point which is located at the zero of the measuring scale.

Example 1.

A mercury barometer reads 28.7 in. of mercury. What is the atmospheric pressure in pounds per square inch?

Solution.

One inch of mercury represents a pressure of 0.491 lb per sq in.; hence 28.7 in. of mercury = 28.7 × 0.491 = 14.1 lb per sq. in.

44. Vacuum.—A vacuum is said to exist in a container when no gas particles are present, and hence there is no pressure in it.

Thus, if the pressure in a container is reduced from atmospheric pressure (14.7 lb per sq in.) to 0 lb per sq in., a **perfect vacuum** is said to exist. In ordinary technical work, however, we do not deal with perfect vacuums because they are impossible to produce. We are concerned with conditions that approach a perfect vacuum as a limit, these being known as partial vacuums. A **partial vacuum** is a condition of reduced pressure below that of the atmosphere. *The amount by which the pressure in the container is reduced below atmospheric pressure is known as the amount of the vacuum, or briefly, as the vacuum.* Hence, the word vacuum is used quantitatively to designate the difference between the atmospheric pressure acting on the outside of the container and the actual pressure acting on the inside of the container. For instance, if the atmospheric pressure is 14.7 lb per sq in., while the pressure on the inside of the container is 10 lb per sq in., the vacuum in the container is $14.7 - 10 = 4.7$ lb per sq in.

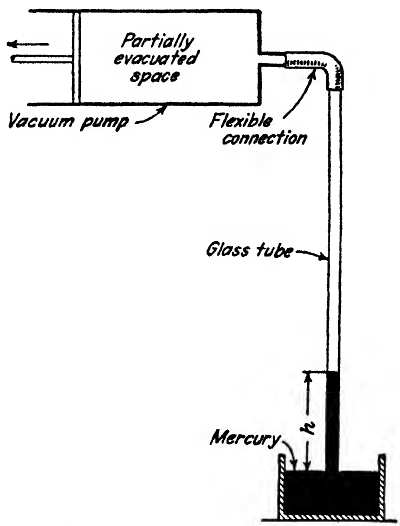


FIG. 20.—Simple method of measuring vacuum.

Vacuum measurements may be made by connecting a glass tube, one end of which is dipped into a bath of mercury, to the vessel containing a vacuum, as shown in Fig. 20. A lowering of the pressure in the container will result in a lowering of the pressure in the glass tube, but the constant atmospheric pressure on the surface of the mercury bath will force mercury up into the tube to a height, h, which balances the difference in pressure between that of the atmosphere and that in the container. If all the pressure were removed from the container, the mercury column would stand about 30 in. high, and we would have a perfect vacuum. If the mercury column stood only 10 in. high, a partial vacuum of 10 in. of mercury would be present.

The actual pressure in the partially evacuated space would equal:

$$14.7 - (10 \times 0.491) = 9.79 \text{ lb per sq in. abs.}$$

Example 1.

A vacuum gage reads 24 in. of mercury when connected to a condenser. If the atmospheric pressure is 14.7 lb per sq in., what is the absolute pressure in the condenser?

Solution.

Pressure in condenser $= 14.7 - (24 \times 0.491) = 2.9$ lb per sq in. abs.

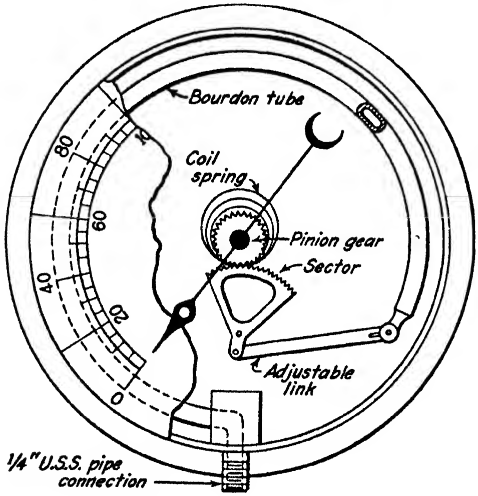


FIG. 21.—Internal construction of Bourdon tube pressure gage.

45. Gage Pressure and Absolute Pressure.—Pressure is ordinarily indicated by a gage. Fig. 21 shows a Bourdon tube pressure gage, with the dial partially removed. The pressure connection is made through the gage case to one end of the Bourdon tube. The Bourdon tube is constructed of tempered copper or steel of oval cross-section, and bent into the arc of a circle. The other end of the tube is closed and free to move. If the pressure in the tube increases, the tube tends to straighten out, thus moving the link fastened to its free end. This link is connected to an adjustable arm of a toothed sector which operates a small pinion gear mounted on the shaft to which the pointer is attached. This pointer, or hand, moves over a dial graduated in pounds per square inch. Thus when the free end of the Bourdon tube moves, owing to a change in pressure, the shaft to which the gage hand is fastened also moves. A hair spring is attached to the pinion shaft to keep the gear teeth in tight contact, and thus compensate for lost motion.

All pressure gages of this type indicate pressures above that of the atmosphere. Hence, if a steam gage shows a pressure of 100 lb per sq in., it merely tells us that the pressure of the steam in the boiler to which the gage is connected is 100 lb per sq in. above the atmospheric pressure that existed at the time the observation was made. The total pressure above 0 lb per sq in. would be equal to the sum of the gage pressure and the atmospheric pressure. If the atmospheric pressure is, say, 14.6 lb per sq in. when the steam gage reads 100 lb per sq in., the corresponding total pressure is $100 + 14.6 = 114.6$ lb per sq in. This total pressure is referred to as the *absolute pressure* of the steam. Thus:

$$\text{Absolute pressure} = \text{Gage pressure} + \text{Atmospheric pressure.} \quad (14)$$

Example 1.

The pressure of the steam in a certain boiler was 230 lb per sq in. gage. The barometer showed a height of mercury of 29 in. when the steam gage was read. What is the absolute boiler pressure for these conditions?

Solution.

$$\begin{aligned} \text{Atmospheric pressure} &= 29 \times 0.491 = 14.24 \text{ lb per sq in.} \\ \text{Absolute boiler pressure} &= 230 + 14.24 = 244.24 \text{ lb per sq in.} \end{aligned}$$

46. The Manometer.—A device commonly used for the measurement of *small* pressures is the open-tube manometer, as shown in Fig. 22. It consists essentially of a piece of glass tubing, bent into the shape of a U, which is partially filled with water, mercury,

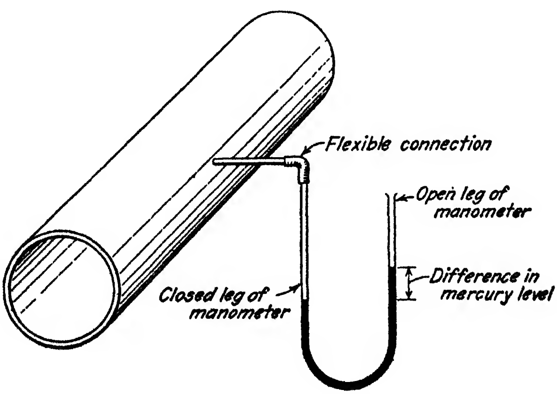


Fig. 22.—Method of measuring pressure in a gas main with an open tube manometer.

or some other liquid. One leg of the U tube is left open to the atmosphere; the other one is connected to the vessel in which the pressure is to be measured.

With equal pressures on the surface of the liquid of each leg of the manometer U tube the liquid level will remain undisturbed. Upon the application of a positive pressure to the leg connected to the container, the liquid in this leg will be depressed and the liquid level in the open tube will rise. The vertical distance in inches between these two liquid levels multiplied by the weight per cubic inch of the liquid (0.491 for mercury and 0.0362 for water) gives the unit pressure in the container *above atmospheric pressure.*

If the closed leg of the manometer is connected to a container in which there is vacuum, the greater pressure of the atmosphere pressing downward on the open leg will cause the liquid level to rise in the closed tube and fall in the open tube. The difference in level times the weight per cubic inch of the liquid is equal to the pounds per square inch of vacuum. This, subtracted from the atmospheric pressure, gives the absolute pressure in the container.

Example 1.

An open water manometer shows a difference in level of 15 in. of water when connected to vessel under pressure. (*a*) What is the pressure in the vessel above that of the atmosphere? (*b*) If the barometer reads 30 in. of mercury, what is the absolute pressure in the vessel?

Solution.

(*a*) Pressure in vessel above atmosphere

$$= 15 \times 0.0362 = 0.544 \text{ lb per sq in.}$$

(*b*) Absolute pressure in vessel

$$= 0.544 + (30 \times 0.491) = 15.27 \text{ lb per sq in.}$$

47. Compression and Expansion of Gases.—From our common experience we know that air, like any other gas, is readily compressible. Every time we inflate an automobile tire by means of an air pump, we compress the air in the pump in order to force it into the tire. It is quite easy to compress a given volume of air to one-half, one-quarter, or one-eighth of its original volume. We also know that, as soon as the force compressing the air is released, the gas will expand immediately to its original volume. Thus if we compress a quantity of air in a tire pump and release the handle when the piston is near the bottom of the stroke, the expansion of

the air will cause the handle of the pump to move back to its original position.

This readiness of air to expand and contract under the action of pressure does not represent a peculiar characteristic of air alone; all gases will be found to perform in much the same manner.

In compressing the gas, the force acting on the pump handle moves through a certain distance, thus doing work on the gas to compress it. Hence, external work is required to compress a gas. When the compressed gas expands, the amount of work put into the gas to compress it is returned. This phenomenon of a gas doing work by expansion is important since it underlies the operation of all heat engines.

48. Boyle's Law.—During the latter part of the seventeenth century Robert Boyle conducted a series of experiments to determine the relation between the pressure exerted on a confined body of gas and its volume. He learned that, if he doubled the absolute pressure of the gas while keeping it at a constant temperature, the volume that the gas occupied was halved. If he tripled the absolute pressure, the volume of the gas would become one-third of its original volume, and so on. Thus, he concluded that *the volume of a given quantity of gas varies inversely with its absolute pressure, provided the temperature of the gas is kept constant.*

This may be expressed in the form of an equation, as follows:

$$P_1V_1 = P_2V_2 = \text{a constant} \quad . \quad . \quad . \quad . \quad (15)$$

where

P_1 = original absolute pressure of the gas, lb per sq in.
V_1 = original volume of the gas, cu ft.
P_2 = final absolute pressure of the gas, lb per sq in.
V_2 = final volume of the gas, cu ft.

A change in the condition of a gas which occurs at constant temperature is known as an **isothermal** change. It will be observed that the weight of the gas undergoing an isothermal change remains the same throughout the process; thus, the density of the gas must change (density being defined as weight per unit volume). For example, doubling the pressure of a given weight of gas will double its density, etc. Hence, we may say that *the pressure exerted by a gas is in direct proportion to its density, provided that the temperatures remains constant.*

Example 1.

What is the final volume when 100 cu ft of air under a pressure of 35 lb per sq in. abs is expanded to a pressure of 20 lb per sq in. abs, the temperature remaining constant?

Solution.

$$P_1 = 35 \text{ lb per sq in. abs.}$$
$$V_1 = 100 \text{ cu ft.}$$
$$P_2 = 20 \text{ lb per sq in. abs.}$$
$$V_2 = \text{unknown.}$$

$$P_1V_1 = P_2V_2$$
$$35 \times 100 = 20 \times V_2$$

$$V_2 = \frac{35 \times 100}{20} = 175 \text{ cu ft.}$$

49. Charles' Law.—If a given weight of gas confined under conditions of fixed or constant pressure is heated, it is found to

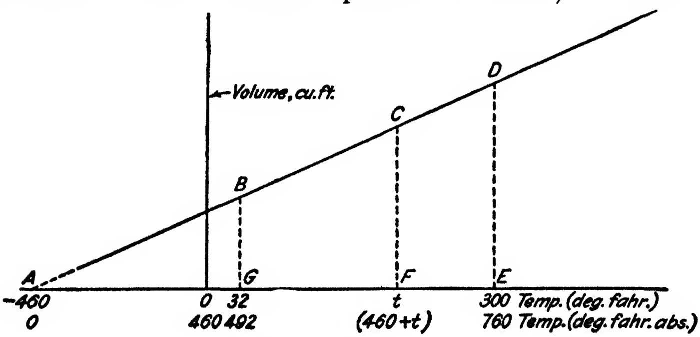


FIG. 23.—Temperature-volume curve for the expansion of a perfect gas.

expand a certain definite amount for each degree rise in temperature. Conversely, it contracts the same definite amount for each degree fall in temperature. Fig. 23 shows a graph plotted from values of volume and temperature taken during such an experiment; temperature in degrees Fahrenheit is plotted on the horizontal axis, and the volume of the gas in cubic inches is shown on the vertical axis. Thus DE represents the volume of the gas at 300 deg fahr, BG the volume at 32 deg fahr, CF the volume at t deg fahr, etc. It will be noticed that the volume of the gas appears to become zero when a temperature of -460 deg fahr is reached.

We see from geometry that the triangles ABG, ACF, and ADE are all similar; therefore

$$\frac{BG}{AG} = \frac{CF}{AF} = \frac{DE}{AE}, \text{ etc.}$$

Hence, it may be stated that the volume of the gas is in direct proportion to its temperature above −460 deg fahr. The temperature of a gas above −460 deg fahr is known as its **absolute temperature.** Thus, if the observed temperature of the gas were 300 deg fahr, its absolute temperature = 300 + 460 = 760 deg fahr.

Now, if we let V be the volume of the gas, and T its absolute temperature above −460 deg fahr, we may say,

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \qquad (16)$$

where

V_1 = original volume of the gas, cu ft.
T_1 = original absolute temperature of the gas, deg fahr abs.
V_2 = final volume of the gas, cu ft.
T_2 = final absolute temperature of the gas, deg fahr abs.

The foregoing formula is a statement of the Law of Charles, which may be expressed verbally by saying that *the volume of a given weight of a gas confined at constant pressure is proportional to its absolute temperature.*

The temperature of −460 deg fahr is known as the point of **absolute zero** on the Fahrenheit scale. This point is 460 + 32 = 492 deg below the freezing point. Hence the absolute zero on the Centigrade scale is (492 × 5/9) = 273 Centigrade degrees below the freezing point, which corresponds to a temperature of −273 deg cent. Therefore observed Centigrade temperatures may be converted into absolute Centigrade temperatures by adding 273 to the observed reading.

A temperature of −460 deg fahr has never been attained, but the inference has been naturally drawn from the curve of Fig. 23 that −460 deg fahr is the lowest possible temperature. It is both natural and convenient to adopt a temperature scale with this point as zero. This scale is known as the Absolute Fahrenheit temperature scale.

Example 1.

If a given weight of hydrogen has a volume of 45 cu ft at 40 deg fahr, what volume would it occupy at 90 deg fahr if the pressure did not change?

Solution.

$$V_1 = 45 \text{ cu ft.}$$
$$T_1 = 40 + 460 = 500 \text{ deg fahr abs.}$$
$$V_2 = \text{unknown.}$$
$$T_2 = 90 + 460 = 550 \text{ deg fahr abs.}$$
$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$
$$\frac{45}{500} = \frac{V_2}{550}$$
$$V_2 = \frac{550 \times 45}{500} = 49.5 \text{ cu ft.}$$

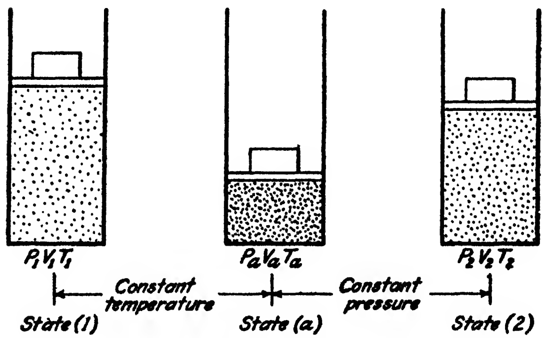


Fig. 24.—Expansion of a perfect gas (1) at constant temperature and (2) at constant pressure.

50. General Gas Law Equation.—The laws of Boyle and Charles may be combined in the following manner to obtain a very useful expression known as the **general gas law equation.** Referring to Fig. 24, let us consider that a given weight of gas undergoes first a change from state (1) to state (*a*), its temperature remaining constant; and secondly that from state (*a*) it expands to state (2), its pressure remaining constant.

Note: $T_1 = T_a$, since the change from (1) to (*a*) takes place at constant temperature.

$P_a = P_2$ since the change from (*a*) to (2) takes place at constant pressure.

From the law of Boyle, we have:

$$P_1V_1 = P_aV_a; \quad \text{but} \quad P_a = P_2;$$

therefore

$$P_1V_1 = P_2V_a,$$

or

$$V_a = \frac{P_1V_1}{P_2}$$

From the Law of Charles, we have:

$$\frac{V_a}{T_a} = \frac{V_2}{T_2}$$

but $T_a = T_1$; therefore

$$\frac{V_a}{T_1} = \frac{V_2}{T_2}$$

or

$$V_a = \frac{T_1V_2}{T_2}$$

but

$$V_a = V_a$$

hence

$$\frac{P_1V_1}{P_2} = \frac{T_1V_2}{T_2}$$

or transposing:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \quad \ldots\ldots\ldots\ldots \quad (17)$$

where

P_1 = original absolute gas pressure, lb per sq in. abs.
V_1 = original gas volume, cu ft.
T_1 = original absolute gas temperature, deg fahr abs.
P_2 = final absolute gas pressure, lb per sq in. abs.
V_2 = final gas volume, cu ft.
T_2 = final absolute gas temperature deg fahr abs.

Since

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

then PV/T = a constant for any point during the expansion or contraction of the gas. This constant is usually designated by the

letter R. The value of R depends entirely upon the nature of the gas. Values of R for some of the more common gases will be found in Table III.

TABLE III

PROPERTIES OF COMMON GASES

Gas	Chemical Symbol	Density, lb per cu ft	Specific Heat		$n = \frac{S_p}{S_v}$	R
			Constant Pressure, S_p	Constant Volume, S_v		
Acetylene......	C_2H_2	0.0725	0.350	0.270	1.280	59.37
Air............	.....	0.0807	0.2375	0.1689	1.406	53.37
Carbon dioxide..	CO_2	0.1227	0.2169	0.167	1.299	38.82
Carbon monoxide	CO	0.0781	0.2450	0.174	1.408	55.24
Ethane.........	C_2H_6	0.0838				
Ethylene.......	C_2H_4	0.0780	0.4040			
Hydrogen......	H_2	0.0056	3.409	2.412	1.413	775.66
Methane.......	CH_4	0.0447	0.5930	0.450	1.320	96.31
Nitrogen.......	N_2	0.0783	0.2438	0.1727	1.412	55.32
Oxygen.........	O_2	0.0892	0.2175	0.1551	1.402	48.55
Sulphur dioxide..	SO_2	0.1786	0.154	0.123	1.250	24.10
Ammonia.......	NH_3	0.0476	0.523	0.399	1.310	90.50

Values taken at 32 deg fahr and 14.7 lb per sq in. abs pressure.

Example 1.

An air compressor cylinder contains 2 cu ft of air when the piston is at a certain distance from the cylinder head. The air pressure is 40 lb per sq in. abs and the temperature is 85 deg fahr at this point. The piston moves toward the cylinder head, compressing the air to a volume of 1.2 cu ft with a resulting pressure of 70 lb per sq in. abs. What is the temperature of the air at the second point?

Solution.

$P_1 =$ 40 lb per sq in. abs.
$V_1 =$ 2 cu ft.
$T_1 = 85 + 460 = 545$ deg fahr abs.
$P_2 =$ 70 lb per sq in. abs.
$V_2 =$ 1.2 cu ft.
$T_2 =$ unknown.

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$\frac{40 \times 2}{545} = \frac{70 \times 1.2}{T_2}$$

$$T_2 = \frac{545 \times 70 \times 1.2}{40 \times 2} = 572 \text{ deg fahr abs.}$$

$$t = 572 - 460 = 112 \text{ deg fahr.}$$

51. Constant Volume Changes.—Consider a gas confined in a closed container such as a tank. If this gas is heated its pressure will be found to increase, but its volume must remain the same, since it is confined to the inside of the tank. This illustrates a condition of expansion of a gas under conditions of constant volume. Taking the equation $P_1V_1/T_1 = P_2V_2/T_2$, and letting

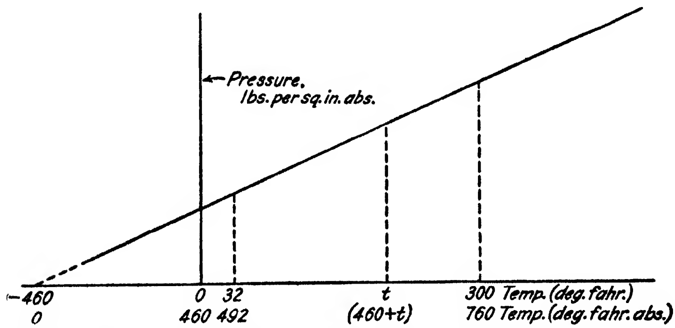


FIG. 25.—Pressure-temperature curve for the expansion of a perfect gas.

$V_1 = V_2$, the volume of the gas cancels out as an essential factor in the equation, leaving

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}. \quad \ldots \ldots \ldots \quad (18)$$

Thus, we may say that, *when a gas is confined to a constant volume, its absolute pressure varies directly with its absolute temperature*:

This law is expressed graphically by the curve shown in Fig. 25.

In constructing this curve, a given weight of gas was kept at constant volume while its temperature was varied. Readings of gas pressure and temperature, taken at regular intervals, were used to plot the curve shown. Vertical distances represent absolute gas pressures in pounds per square inch, and horizontal distances represent absolute gas temperatures in degrees Fahren-

heit. It should be noticed that this curve resembles the one plotted in Fig. 23 for Charles' Law. From similar triangles, as in Charles' Law, Article 49, we may say that the absolute gas pressure varies directly with the absolute temperature of the gas at any point, since the curve cuts the temperature axis at -460 deg fahr, the zero of the absolute temperature scale.

Example 1.

A closed tank contains 180 cu ft of air under a pressure of 80 lb per sq in. gage and at 75 deg fahr. If the tank is heated to 125 deg fahr, what will be the resulting air pressure as read by the gage? Assume normal atmospheric pressure.

Solution.

Volume of gas remains constant.

$$P_1 = 80 + 14.7 = 94.7 \text{ lb per sq in. abs.}$$
$$T_1 = 75 + 460 = 535 \text{ deg fahr abs.}$$
$$P_2 = \text{unknown.}$$
$$T_2 = 125 + 460 = 585 \text{ deg fahr abs.}$$

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$$\frac{94.7}{535} = \frac{P_2}{585}$$

$$P_2 = \frac{94.7 \times 585}{535} = 103.7 \text{ lb per sq in. abs.}$$

$$P_2 = 103.7 - 14.7 = 89 \text{ lb per sq in. gage.}$$

52. Air Thermometer.—Fig. 26 shows an apparatus known as a **constant-volume air thermometer.** It consists essentially of a bulb containing dry air to which are connected two glass tubes containing mercury, one of which may be lowered or raised as desired. These glass tubes are joined at the bottom with rubber tubing. The glass bulb is placed in the space whose temperature is to be measured, and the open mercury tube is adjusted until the mercury in the closed tube is restored to its original level. This restores the volume of the air in the bulb to its original volume. Knowing the original temperature of the air in the bulb, as well as the original absolute pressure, we may calculate the final temperature after obtaining the final absolute pressure. The absolute pressure of the air in the bulb at any time is equal to the barometer

reading ± the difference in level of the mercury in the tubes. Hence, starting with a known temperature, we may obtain the final temperature by the equation $P_1/T_1 = P_2/T_2$. The original temperature most frequently selected is 32 deg fahr, and is obtained by surrounding the air bulb with broken ice. This eliminates the necessity of using a mercury thermometer to obtain the original temperature.

This type of thermometer serves a very useful purpose in

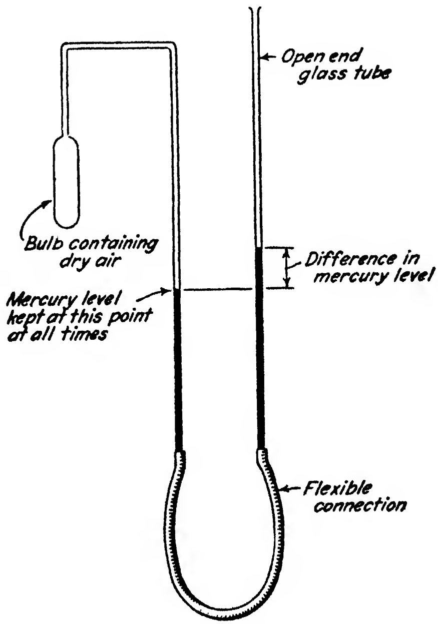


FIG. 26.—Constant volume air thermometer.

making accurate measurements of temperatures that are above and below the range of the ordinary mercury thermometer.

Example 1.

When the bulb of an air thermometer is surrounded with melting ice the mercury level is 1 in. higher in the open tube than in the tube attached to the air bulb. When the bulb is surrounded by steam of unknown temperature the mercury in the open tube stands 18 in. above the level in the closed tube, that is, after the mercury level in the closed tube has been returned to its original position. Determine the temperature of the steam. Barometer reading = 30 in. of mercury.

Solution.

$$P_1 = 1 + 30 = 31 \text{ in. of mercury absolute.}$$
$$T_1 = 32 + 460 = 492 \text{ deg fahr abs.}$$
$$P_2 = 18 + 30 = 48 \text{ in. of mercury absolute.}$$
$$T_2 = \text{unknown.}$$

Volume of air in bulb is held constant.

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$$\frac{31}{492} = \frac{48}{T_2}$$

$$T_2 = \frac{492 \times 48}{31} = 761 \text{ deg fahr abs.}$$

$$t = 761 - 460 = 301 \text{ deg fahr.}$$

53. Consideration of the Weight of Gas.—From the general gas law equation we learned that PV/T = a constant. If the constant for one pound of gas be called R, the resulting equation for one pound of gas becomes $PV/T = R$, or $PV = RT$; and for any weight of gas, W,

$$PV = WRT \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

in which

W = weight of gas, lb.
P = absolute gas pressure, lb per sq ft.[1]
V = volume of gas, cu ft.
T = absolute temperature of gas, deg fahr.
R = constant for any given gas. Values of R are given in Table III.

The value of R may be calculated from the observed density of the gas under standard conditions. Thus, for air, since one cubic foot weighs 0.0807 lb (Table III)

$$R = \frac{PV}{WT} = \frac{(14.7 \times 144) \times 1}{0.0807 \times (32 + 460)} = 53.37$$

[1] It should be noticed that P in this equation is expressed as pounds per square foot instead of pounds per square inch as in all the foregoing work. To change pounds per square inch to pounds per square foot, simply multiply the former by 144. This departure is necessary since the values of R as given in Table III have been calculated using P in pounds per square foot, which follows the customary method of procedure.

In a similar manner, the values of R for the other gases listed in Table III were calculated.

Example 1.

From Table III it is found that the density of oxygen at a pressure of 14.7 lb per sq in. is 0.0892 lb per cu ft, provided the temperature is 32 deg fahr. What is the value of R for oxygen?

Solution.

$$R = \frac{PV}{WT} = \frac{(14.7 \times 144) \times 1}{0.0892(32 + 460)} = 48.4$$

Example 2.

What is the density of dry air at 80 deg fahr and atmospheric pressure?

Solution.

P = absolute pressure of gas, lb per sq ft = 14.7×144.
V = volume of gas, cu ft = 1.
W = weight of gas, lb = unknown.
T = absolute temperature of gas, deg fahr = $80 + 460$.
R = 53.37 (Table III).

$$W = \frac{PV}{RT} = \frac{14.7 \times 144 \times 1}{53.37(80 + 460)} = 0.0735 \text{ lb.}$$

Thus the weight of 1 cu ft (density) of air under these conditions = 0.0735 lb.

54. Density of Gases.—The *density of any substance is its weight per unit of volume, i.e., pounds per cubic foot.* Thus the density of any substance is numerically equal to the total weight of the substance divided by its total volume. Hence in the English system we have the following:

$$D = \frac{W}{V} \qquad (20)$$

in which

D = density of substance, lb per cu ft.
W = weight of substance, lb.
V = volume of substance, cu ft.

Example 1.

If 10 cu ft of water weigh 624 lb, what is the density of the water?

Solution.

$$D = \frac{W}{V} = \frac{624}{10} = 62.4 \text{ lb per cu ft.}$$

Example 2.

If 100 cu ft of dry air weigh 8.07 lb, what is the density of the air?

Solution.

$$D = \frac{W}{V} = \frac{8.07}{100} = 0.0807 \text{ lb per cu ft.}$$

We have learned that when a solid substance is heated it expands, and when cooled it contracts. Thus a change in temperature of a solid substance will effect a change in the volume of the substance without ordinarily changing its weight. Hence if a solid is heated its volume will increase, thereby decreasing the density of the solid.

With gases it has been found that other factors besides temperature have a bearing on the volume occupied by a unit weight of gas. The facts involved are: (1) the absolute pressure, (2) the value of R, and (3) the absolute temperature. This may be shown as follows:

$$PV = WRT$$

but density $= W/V$. Then density of a gas is

$$D = \frac{P}{RT} \quad \ldots\ldots\ldots \quad (21)$$

in which

D = density of gas, lb per cu ft.
P = absolute pressure of gas, lb per sq ft.
R = constant, depending on the kind of gas, Table III.
T = absolute temperature of gas, deg fahr.

Example 1.

Air is confined in a tank under a pressure of 130 lb per sq in. abs and at 80 deg fahr. What is the density of the air?

Solution.

$$D = \frac{P}{RT} = \frac{130 \times 144}{53.37 \times (80 + 460)} = 0.65 \text{ lb per cu ft.}$$

SUMMARY OF CHAPTER III

The COEFFICIENT OF LINEAR EXPANSION of a solid defines the rate of increase of length due to a rise of temperature. Numerically it is obtained by dividing the increase in length by the original length and by the increase in temperature, thus:

$$\textbf{Coefficient of linear expansion} = \frac{\textbf{Increase in length}}{\textbf{Original length} \times \textbf{Rise in temperature}}.$$

For the **COEFFICIENT OF EXPANSION OF AN AREA**, twice the linear coefficient may be used, if the body expands at a uniform rate along all axes.

The **COEFFICIENT OF CUBICAL EXPANSION**, under similar circumstances, may be taken as three times the linear coefficient.

The **APPARENT COEFFICIENT OF EXPANSION** of a liquid differs from the true coefficient by the amount of the coefficient of cubical expansion of the containing vessel.

Pressure: **UNIT PRESSURE** is the force applied to a unit area of a surface.

Conversion Units:

One-foot head of water = 0.433 lb per sq in.
One-inch head of mercury = 0.491 lb per sq in.

STANDARD CONDITIONS: The air surrounding the earth bears down on all objects with a unit pressure of 14.7 lb per sq in. at 32 deg fahr and at sea level. These values of pressure and temperature have been selected to represent " standard conditions."

A pressure gage reads the pressure above that of the atmosphere. Thus, to obtain the absolute pressure, the atmospheric pressure must be added to the gage reading; hence,

$$\text{Absolute pressure} = \text{Gage pressure} + \text{Atmospheric pressure.}$$

When the pressure in a vessel is lower than that of the atmosphere, a vacuum is said to be present inside the vessel. A **PERFECT VACUUM** would exist if the pressure inside the vessel were zero. Any other condition of vacuum is known as a **PARTIAL VACUUM**. The difference between the atmospheric pressure and the absolute pressure inside the vessel is known as the vacuum. Vacuum is usually measured in inches of mercury.

A **MANOMETER** is a mercury gage used for the measurement of small pressures.

ABSOLUTE TEMPERATURE.—The absolute zero of temperature is estimated to be at a point 460 deg fahr below the zero on the Fahrenheit thermometer scale. At a temperature of −460 deg fahr a gas is considered to have zero volume. Hence, to convert observed Fahrenheit temperatures to absolute Fahrenheit temperatures, 460 deg fahr must be added to the observed reading; thus:

$$\text{Absolute Fahrenheit temperature} = \text{Observed Fahrenheit temperature} + 460.$$

The expansion of a perfect gas obeys the following law, provided that the gas temperature is far removed from the temperature of liquefaction for the gas:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

The equation PV = WRT may be used to determine the weight of a given volume of gas confined under known conditions of temperature and pressure. It should be remembered in using this equation that P is expressed in pounds per square foot instead of the customary pounds per square inch. The values of R, a constant depending on the nature of gas, may be found in Table III. This equation may also be used to determine the density of a gas, that is, its weight per unit of volume.

REVIEW PROBLEMS ON CHAPTER III

1. A piece of cast brass pipe is 50 ft long at 70 deg fahr. How many inches will this pipe expand when heated to 300 deg fahr?

2. A 10-ft bar of brass is placed side by side with an equal length bar of steel. If both bars undergo a temperature change of 250 deg fahr, which will be the longer, and by how many inches?

3. A hollow glass sphere which will break at a pressure of 125 lb per sq in. abs is filled with atmospheric air at a temperature of 70 deg fahr. At what temperature will the glass sphere break because of expansion of the confined air?

4. A steel tire is exactly 5 ft in inside diameter when at a temperature of 70 deg fahr. This tire is to be shrink-fitted to a wheel having an outside diameter of 5.0625 ft. To what temperature must the tire be heated?

5. A tank whose base dimensions are 12 ft by 4 ft is 7 ft high. If it is filled to the top with water at room temperature, what is the resulting pressure in pounds per square inch acting on the bottom of the tank? What height of mercury would produce this same pressure on the bottom of the tank?

6. An automobile service station is equipped with a tank $1\frac{1}{2}$ ft in diameter and 5 ft long for the storage of air. The air for the tank is taken from a room at 78 deg fahr and pumped into the tank until a pressure of 120 lb per sq in. abs and a temperature of 150 deg fahr is reached. How many cubic feet of atmospheric air are required to completely fill the tank under these conditions?

7. A volume of 20 cu ft of gas is confined under "standard conditions." If this gas is compressed to a volume of 4 cu ft and to a temperature of 100 deg fahr, what is the resulting absolute pressure?

8. If a certain gas at atmospheric pressure is compressed to one-fourth its original volume, what is the absolute pressure that results? Assume temperature to remain constant.

9. The mercury levels in both legs of an air thermometer are at the same height when the bulb of the instrument is immersed in melting ice at standard atmospheric pressure. When the bulb is immersed in steam of unknown temperature the mercury in the open leg rests 25 in.

above the level in the closed tube, after the level in the closed tube is restored to its original position. Determine the temperature of the steam.

10. A volume of 8.35 cu ft of sulphur dioxide weighs 3 lb when subjected to a pressure of 30 lb per sq in. abs and a temperature of 40 deg fahr. Find the value of R for sulphur dioxide.

11. Six pounds of air at 90 deg fahr are contained in a tank 3 ft by 3 ft by 4 ft. What is the pressure of the air in pounds per square inch gage?

12. An open-tube manometer is connected to a gas main. The mercury in the open tube is 5 in. higher than in the closed tube. Determine the absolute pressure of the gas in the main.

13. A given quantity of air is heated to 105 deg fahr when under a pressure of 50 lb per sq in. gage. Barometer reading, 28.9 in. of mercury. Determine the density of the air under these conditions.

14. A 4-lb bar of brass is 3 in. by 4 in. by 6 in. when at a temperature of 70 deg fahr. What will be its density when heated to 400 deg fahr?

CHAPTER IV

THREE STATES OF MATTER

55. Three States of Matter.—Matter exists in three different states, namely, as solids, liquids, and gases. Thus, we speak of iron as a solid, oil as a liquid, and air as a gas. We are also aware that most of the substances of our common experience may exist in all three states, temperature being the chief factor determining in which of the three states the substance will be. Water serves as the common example in that it exists as ice, water, or steam. If, however, we studied the states in which other substances may exist, we should find that all of them (with a few doubtful exceptions) have three states, if the proper conditions of pressure and temperature are secured. For example, hydrogen, normally considered a gas, may be liquefied at a temperature of −422 deg fahr; pure iron, normally a solid, may be liquefied at 2780 deg fahr, and ultimately changed into a gas by the further application of heat. Thus, we say that if heat is applied to any solid material it will pass through three successive states, namely, solid, liquid, and gaseous.

56. Fusion.—If a solid element, such as lead, is heated, its temperature is found to increase at a uniform rate until a certain point is reached at which the lead changes from the solid to the liquid state. During the time required to complete this change of state the temperature of the lead remains practically constant. This constant temperature is known as the melting temperature of the lead, or briefly its **melting point.** Hence, *melting or fusion is the process by which a substance is changed from the solid to the liquid state by the addition of heat; and the temperature at which this change takes place is known as the melting point of the substance.*

The melting temperature of a substance is usually very definite, and entirely independent of the direction of change. For example, solid lead will melt at the same temperature that liquid lead will solidify; water freezes at the same temperature at which ice melts, etc.

57. Heat of Fusion.—It has been found that when a solid substance is heated its temperature rises continuously until the melting point is reached, at which point the temperature remains constant until the entire solid mass has changed to a liquid. After fusion, the temperature rises again, but the rate of rise above the melting point will be found to differ from the rate of temperature change up to the melting point. This change in the rate of heating is due to a change in the specific heat of the substance, that is, the specific heat of the liquid after fusion is different from the specific heat of the solid before fusion. For example, the specific heat of ice is about half that of water.

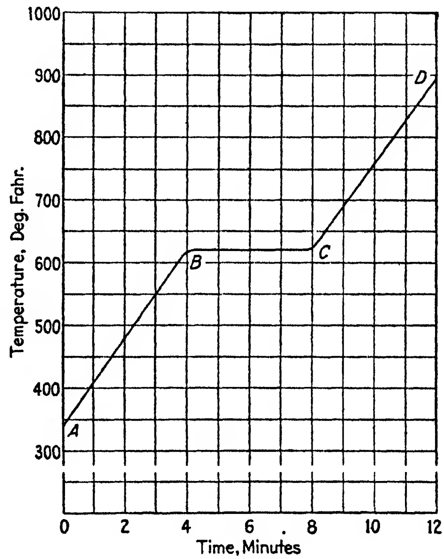


FIG. 27.—Fusion curve for lead.

Fig. 27 illustrates the method of determining the fusion temperature of lead by plotting a heating curve from the readings of a thermometer which has been imbedded in the solid. Temperature is plotted on the vertical axis against time on the horizontal axis.

Two pounds of lead are heated in a small crucible, and readings of temperature are taken every minute during the heating until after the bend BC in the heating curve has been fully passed. AB shows the rise in temperature of the solid; BC shows a condition of steady temperature while liquefaction is taking place; and CD shows the rise in temperature of the liquid after melting is complete. The melting temperature of the lead corresponds to the temperature on the vertical axis opposite the horizontal line BC, namely, 620 deg fahr.

The heat absorbed per minute by the 2 lb of lead may be computed by noting that the temperature rises at the rate of approximately 70 deg fahr per min from A to B. Since the

specific heat of lead is 0.032 (Table I, Chapter I), the quantity of heat received per minute is $0.032 \times 2 \times 70 = 4.48$ Btu; or approximately 4.5 Btu per min.

It will be noticed that a certain amount of heat is supplied to the lead during the 4-min interval from B to C but that during this period no change in temperature occurs. Assuming that the heat is supplied at the rate of 4.5 Btu per min as before, the lead will absorb $4.5 \times 4 = 18$ Btu during this period of stationary temperature. That is, each pound of lead requires $18/2 = 9$ Btu to change from the solid to the liquid state. *The quantity of heat required to change one pound of a substance from the solid to the liquid state, or vice versa, without change in temperature, is known as the latent heat of fusion of the substance.* Thus we say, the latent heat of fusion for lead is 9 Btu per lb, since this is the quantity of heat that must be imparted to one pound of lead at the melting point in order to completely change the lead from the solid state to the liquid state.

It is found by experiment that the latent heat of fusion is different for each substance, and that the value for any one substance will vary slightly according to the pressure acting on the substance. This effect of pressure on the freezing point of most materials is so small, however, that it may be neglected for all practical purposes. Table IV gives the latent heat of fusion of a few of the more common substances.

TABLE IV

HEAT OF FUSION OF VARIOUS MATERIALS

(Btu per pound)

Aluminum	126.0	Nickel	133.0
Copper	77.5	Sulphur	15.8
Ice	144.0	Tin	25.0
Lead	9.0	Zinc	47.0
Mercury	5.4		

Example 1.

What quantity of heat is required to melt 6 lb of ice at 32 deg fahr. into water at 32 deg fahr?

Solution.

$$6 \times 144 = 864 \text{ Btu.}$$

Example 2.

If 60 lb of ice at 22 deg fahr is changed into water at 70 deg fahr, how many Btu are supplied? (Specific heat of ice = 0.5.)

Solution.

$$[0.5 \times 60 \times (32 - 22)] + [60 \times 144] + [60 \times (70 - 32)] = 11{,}220 \text{ Btu.}$$

Example 3.

If 2025 Btu are supplied to 10 lb of ice at 15 deg fahr, what will be the resulting temperature?

Solution.

Heat required to bring ice to 32 deg fahr
$= 0.5 \times 10 \times (32 - 15) = 85$ Btu.
Heat required to melt ice $= 10 \times 144 = 1440$ Btu.
Heat left to raise temperature of water
$= 2025 - (1440 + 85) = 500$ Btu.
500 Btu will raise 10 lb of water 50 deg fahr above freezing point.

Thus final temperature of water $= 32 + 50 = 82$ deg fahr.

58. Change of Volume Due to Solidification.—It will be found that most substances contract when they change from the liquid to the solid state. That is to say, one cubic foot of matter in the liquid state will occupy a space of less than one cubic foot after it has solidified. There are a few notable exceptions, for example, water and cast iron, which expand when this change of state occurs. The expansion of water upon freezing often results in the bursting of water pipes in the winter time. The property of the expansion of cast iron serves a very useful purpose in manufacturing this material, since the expansion causes the iron to completely fill the mold in which it is cast. This makes possible the manufacture of sharp-edged castings.

59. Freezing Points of Solutions.—If a solid is dissolved in a liquid, the solid is changed to a liquid, and in so doing absorbs an amount of heat equal to its latent heat of fusion. This heat is obtained from the store of heat in the liquid; thus the liquid is cooled. If a quantity of ice at 32 deg fahr is mixed with an equal quantity of common salt, a similar cooling effect occurs, resulting in a temperature of about 5 deg fahr. If this mixture of salt and water, commonly called brine, is packed around a vessel containing a liquid which freezes at a temperature above 5 deg fahr, the

liquid will be frozen easily. This is one of the commonest and simplest methods of freezing liquids such as ice cream. This principle is also used in storage refrigeration.

60. Freezing and Boiling Points of a Solution.—Water freezes at a temperature 32 deg fahr when under conditions of standard pressure. Salt added to water lowers the freezing point. A typical example of this is the spreading of salt on sidewalks in winter to prevent water from freezing there.

If a dilute solution of salt and water is frozen, pure ice is formed, leaving the entire amount of salt behind in the form of a concentrated solution of salt and water, or brine. Likewise, if a solution of salt and water is boiled, pure steam is formed, and all the salt is left behind in the vessel. If we carefully observe the temperature at which either of these transitions occurs, we find that the water freezes at a temperature lower than the normal freezing point, and boils at a temperature higher than the normal boiling point.

Thus we say that, when a substance such as salt is dissolved in water, its effect is to *raise the boiling point and lower the freezing point* of the water. Dissolved solids producing this effect do not evaporate with the water vapor or crystallize with the ice.

61. Alloys.—Very few of the metallic elements such as iron, copper, lead, etc., are commercially used alone, but are alloyed with other substances to develop special physical properties. For example, iron is mixed with carbon in order to develop special qualities which are not present in pure iron; tin is alloyed with lead to produce an alloy which has distinctly different properties from those of either pure tin or pure lead.

An alloy is a substance formed from the solidification of a liquid solution of two or more metals. Most metals if mixed together in the liquid condition will solidify to form a homogeneous solution which appears to the human eye to be of uniform texture. However, there are a few metals, such as lead and aluminum, that will not alloy, but separate into distinct layers of the two elements upon solidification.

62. Solidification of Alloys.—The melting point of pure lead is 620 deg fahr; that is, a liquid solution of lead solidifies at this temperature. If a quantity of tin is mixed with the lead while it is in the liquid state, it will be found that the transition from the liquid state to the solid state will not occur until the liquid

solution has cooled to some temperature lower than 620 deg fahr. Tin lowers the melting point of the lead in much the same manner as salt lowers the freezing point of water. The solidification of lead and tin is similar to the freezing of water and salt except that both the lead and tin remain together in the solid, whereas the salt does not remain in the ice.

It is found that the melting point of lead is lowered by the addition of tin until a minimum melting point temperature is reached when 69 percent of the mixture is comprised of tin and the remaining 31 percent is lead. To illustrate the effect on the melting point of different percentages of tin in lead, Fig. 28 is presented. Starting with zero percent of tin at the left end of the

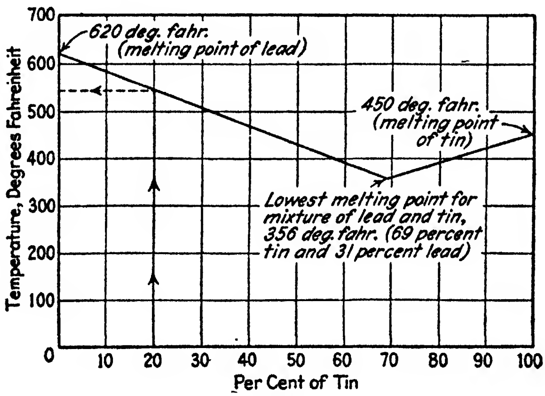


FIG. 28.—Tin-lead equilibrium diagram.

horizontal axis, we find the freezing point to be 620 deg fahr. This is of course the freezing point for pure lead. If we mix 20 percent of tin by weight with the lead, its melting point is lowered to 550 deg fahr. Similarly, if the tin is increased to 40 percent, the melting temperature is lowered to 470 deg fahr as a result. The further addition of tin will continue to lower the melting point until 69 percent of tin by weight has been added, after which any additional amount of tin effects a raising of the fusion temperature. This may be visualized by reference to the graph of Fig. 28, which is called an **equilibrium diagram.**

The lowest temperature at which a liquid mixture of lead and tin can exist, namely 356 deg fahr, is known as the **eutectic temperature** for lead and tin. The mixture of lead and tin that

produces this effect consists of 31 percent lead and 69 percent tin, and this is known as the **eutectic mixture** of lead and tin.

63. Iron-Carbon Equilibrium Diagram.—The process of alloying iron and carbon may be best understood in the light of the iron-carbon diagram which is shown in part in Fig. 29. In this equilibrium diagram, vertical distances represent degrees Fahrenheit, and horizontal distances represent percentages by weight of carbon.

This graph is plotted from an experimental determination of the melting temperature of iron when alloyed with various amounts of carbon up to 5 percent. It is seen from an inspection of the graph that the addition of carbon to iron causes a lowering

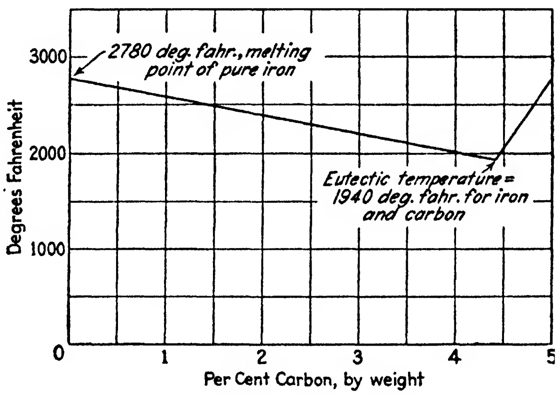


FIG. 29.—Iron-carbon equilibrium diagram.

of the melting point up to 4.3 percent, after which any further addition of carbon raises the melting point. Hence, the eutectic temperature for iron and carbon is 1940 deg fahr; and the eutectic mixture consists of 4.3 percent carbon and 95.7 percent iron.

64. Evaporation.—When a liquid such as water is heated in an open vessel the effect of the heat is first to increase the temperature of the water, and second to evaporate it into steam. If a thermometer is placed in the water, the temperature will be found to rise steadily until the boiling point is reached, after which the temperature will remain constant until all the water has been converted into steam.

If the above experiment were repeated with, say, alcohol, similar results would be obtained. However, it would be found

that the alcohol boiled at a lower temperature than the water, and that less heat was required to completely evaporate an equal weight of it. Similar experiments conducted with other liquids would reveal that all liquids have different evaporation temperatures, and require different amounts of heat to evaporate equal weights of the liquid.

The amount of heat required to completely evaporate one pound of a substance without change in temperature is known as the latent heat of evaporation of that substance.

It should be noticed that all the foregoing experiments were described as taking place in an open vessel so that the pressure acting on the surface of the liquid was the same for all cases, namely, the pressure of the atmosphere.

65. Heat of Evaporation of Water at Atmospheric Pressure.—When one pound of water at 212 deg fahr is converted into one pound of steam at 212 deg fahr, 970.2 Btu are required to produce the change. Thus we say that the latent heat of evaporation for steam generated under conditions of normal atmospheric pressure is 970.2 Btu per lb. If this pound of steam is condensed back into water again, it will be found that 970.2 Btu of heat energy are given up during the liquefaction of the steam.

$$\left.\begin{array}{l}\text{Heat required to evaporate 1 lb of water at}\\ \quad\text{normal atmospheric pressure}\end{array}\right\} = 970.2 \text{ Btu.}$$

$$\left.\begin{array}{l}\text{Heat liberated by the condensation of 1 lb}\\ \quad\text{of steam at normal atmospheric pressure}\end{array}\right\} = 970.2 \text{ Btu.}$$

Example 1.

How many Btu are required to change 8 lb of water at 212 deg fahr into steam at 212 deg fahr under conditions of standard pressure?

Solution.

$$8 \times 970.2 = 7761.6 \text{ Btu.}$$

Example 2.

A steam radiator operating under conditions of atmospheric pressure (0 lb per sq in. gage) condenses 3 lb of steam at 212 deg fahr into water at 212 deg fahr. How many Btu are given off during the condensation?

Solution.

$$3 \times 970.2 = 2910.6 \text{ Btu.}$$

Example 3.

If the condensed water comes from the radiator at a temperature

of 80 deg fahr, what is the total quantity of heat emitted by the radiator due to the condensation of the 3 lb of steam?

Solution.

$$[3 \times 970.2] + [3 \times (212 - 80)] = 3306.6 \text{ Btu.}$$

Example 4.

What quantity of heat would be required to convert 5 lb of ice at 32 deg fahr into steam at 212 deg fahr? Change takes place in an open vessel under conditions of normal atmospheric pressure.

Solution.

$$[5 \times 144] + [5 \times (212 - 32)] + [5 \times 970.2] = 6471.0 \text{ Btu.}$$

Example 5.

If 4 lb of ice at 20 deg fahr is changed into steam at 250 deg fahr, what quantity of heat was supplied? (Specific heat of ice = 0.5; specific heat of steam = 0.48.)

Solution.

$$[0.5 \times 4 \times (32 - 20)] + [4 \times 144] + [4 \times (212 - 32)] + [4 \times 970.2] + [0.48 \times 4(250 - 212)] = 5273.8 \text{ Btu.}$$

66. Effect of Pressure on Boiling Point of Water.—We have learned that the air surrounding us has weight which produces a pressure of 14.7 lb per sq in. at sea level, and 32 deg fahr, and because of its weight it exerts a very definite pressure upon every surface with which it is in contact. We also learned that, if we travel upward from the surface of the earth, the atmospheric pressure decreases as we increase our altitude. If a quantity of water is heated at sea level it boils at a temperature of 212 deg fahr, whereas if it is heated at an altitude of 6000 ft above sea level it will boil at 201 deg fahr. This lowering of the boiling point is due to the decrease in pressure acting on the surface of the water at the higher elevation. The boiling point of water falls approximately one degree Fahrenheit for an increase in elevation of 540 ft.

The temperature at which water will boil depends upon the pressure exerted upon the surface of the water. If this surface pressure is increased, the boiling temperature is increased; and, conversely, if the surface pressure is lowered, the boiling temperature is correspondingly lowered.

To illustrate this, assume that a quantity of water is placed in a closed vessel, and that an absolute pressure of 15.7 lb per sq in. is

exerted on the surface of the water. With sufficient heat applied under the vessel, the water will not boil and start forming steam until a temperature of 215 deg fahr is reached. Likewise, if an absolute pressure of 150 lb per sq in. is acting on the surface of the water, boiling will not take place until a temperature of 358.4 deg fahr is reached. If the pressure in the vessel is reduced to 10 lb per sq in., boiling will occur at 193.2 deg fahr.

67. Condensation.—*Condensation is the reverse process of evaporation.* It is the process by which a gas or vapor is converted into a liquid. When condensation takes place, the latent heat of evaporation must be withdrawn from the vapor before it is entirely converted into the liquid state. A familiar example of this is present in the condensation of steam in an ordinary steam radiator. As the steam is condensed, it gives up its latent heat, which con-

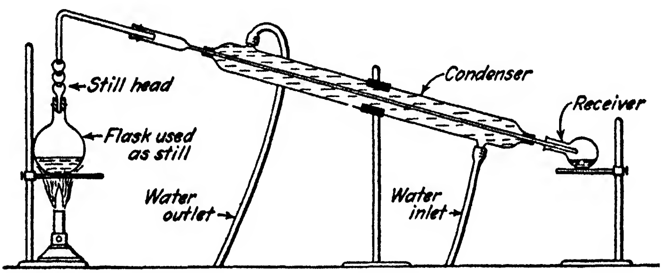


FIG. 30.—Apparatus for distillation.

stitutes the major portion of the heat given off by the radiator. The condensed vapor is called the **condensate.**

68. Distillation.—When it is desired to separate a single liquid from a solution containing two or more liquids of different boiling points, a process called **distillation** is resorted to. Distillation is the process of evaporating a liquid and then condensing the vapor back into a liquid again. The laboratory apparatus used for this process is shown in Fig. 30. This apparatus consists of a flask in which the original solution is heated. This flask is connected to a condensing tube which is surrounded by running water. As the vapor is formed in the flask it passes into the condensing tube, is condensed to a liquid, and flows out into a suitable receiving vessel. Impurities contained in the original solution are left behind in the flask since they have a different evaporation temperature from that of the liquid being distilled. The distilled liquid that is

delivered to the receiving vessel is known as the **distillate.** Distillation is a cycle of operation which is much used either singularly or repeatedly, for the purpose of purifying liquids.

It is evident that, if the original solution consists of several liquids of different evaporation temperatures, each one may be distilled off separately by heating the flask to the successive temperatures corresponding to the boiling points of these liquids. The process of separating several liquids from the original solution in this way is known as **fractional distillation.**

In the process of fractional distillation, heat is applied to the flask until the evaporation temperature at which the liquid having the lowest boiling point is reached. The solution in the flask is kept at this temperature until all the vapor formed is collected in the receiving vessel. Then the temperature is gradually raised to the boiling point of the next higher liquid. After this liquid is completely distilled, the temperature is again raised to distill off the next liquid. This process is continued until all the desired constituents are obtained from the original solution. Crude petroleum is distilled in this manner to obtain the various oils and gasolines, which are passed off in the order of their respective evaporation temperatures.

In some cases, if sufficient heat is applied to the flask to distill a certain liquid from it, undesirable chemical changes will take place in the solution in the flask. In order to prevent this, distillation may be carried on under conditions of reduced pressure. That is, the space above the liquid in the flask is subjected to a partial vacuum, in order that the distillates will evaporate at a lower temperature. This process is known as **vacuum distillation.** Sugar is separated from its syrup in this manner so that the water can be driven off at a temperature that will not affect the chemical composition of the sugar.

Example 1.

How many pounds of water must circulate through a condenser such as shown in Fig. 30 to distill 30 lb of alcohol if the circulating water enters the condensing tube at 40 deg fahr and leaves it at 160 deg fahr? The alcohol leaves the condenser at 60 deg fahr.

Solution.

Considering the latent heat of alcohol as 369 Btu per lb, its boiling point as 159 deg fahr, and its specific heat as 0.59 when in

the liquid state, the quantity of heat that must be extracted from the alcohol vapor in order to condense it

$$= (30 \times 369) + 0.59 \times 30(159 - 60) = 12{,}822.3 \text{ Btu.}$$

Since it is the function of the water to extract this quantity of heat, the following amount of water will be required:

$$12{,}822.3 = W(160 - 40)$$

$$W = \frac{12{,}822.3}{160 - 40} = 106.9 \text{ lb of water.}$$

69. Digesters or Pressure Cookers.—A **digester** is a closed chamber in which cooking is done at a temperature higher than that obtainable under atmospheric conditions. The food to be cooked is placed in the digester, and the cover is sealed tightly in place. As heat is applied, the vapors formed cannot escape from the closed chamber, and therefore the internal pressure is increased. This increase in internal pressure results in a higher boiling point for the liquid, and the process of cooking food is accelerated by this higher temperature. On high mountains, pressure cookers are necessary for domestic cooking, since a temperature high enough to cook the food sufficiently cannot be obtained by any other means. Commercial forms of digesters are used in refuse-disposal plants, in fertilizer plants, in the cooking of bones and meats, and in the extraction of oils, fats, and greases.

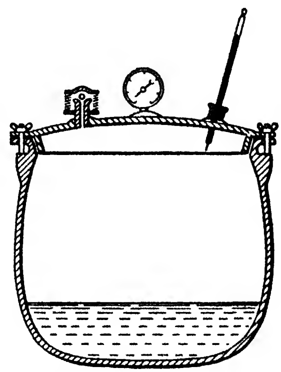


FIG. 31.—Pressure cooker.

Fig. 31 represents a type of pressure cooker which is commonly used in mountainous regions for cooking vegetables and foods that are ordinarily boiled. It is claimed that foods cook very much more quickly at a pressure of about 35 lb per sq in. abs, and require less fuel to complete the operation. The reason for this becomes evident when it is learned that the boiling temperature corresponding to 35 lb per sq in. abs is 259 deg fahr. This slight increase in temperature above 212 deg fahr greatly increases the speed at which the starch grains are broken up, and consequently the time required for cooking is reduced.

STEAM

70. Generation of Steam.—The formation of steam is accomplished by heating water. For the sake of simplicity, let us assume that we start with one pound of water at 32 deg fahr contained in an open vessel subjected to an atmospheric pressure of 14.7 lb per sq in.

As heat is applied to the water its temperature will rise. An increase in temperature of one degree Fahrenheit will result for each Btu added to the water, considering the specific heat of water as unity. This increase in temperature will continue until the boiling point is reached, whereupon the temperature of the water will remain constant until all the water is converted into steam. The quantity of heat supplied to the water between 32 deg fahr and the boiling point is known as the **heat of the liquid.**

When the temperature of the water reaches the boiling point, bubbles of steam form at the bottom of the vessel at the point of application of heat. These bubbles, being lighter than water, rise to the surface and discharge the steam which they contain. The temperature at which this action occurs depends solely upon the pressure to which the water is subjected. In the case being considered, boiling takes place at 212 deg fahr, whereas if the pressure acting on the surface of the water were 260 lb per sq in. abs, boiling would not occur until a temperature of 404.4 deg fahr were reached. However, if the pressure were lowered to 5 lb per sq in. abs the water would boil when the temperature reached 162.2 deg fahr. The steam formed in each case will be at the same temperature as that of the water at the boiling point. Steam whose temperature is the same as that of the water from which it is formed is known as **saturated steam.** Saturated steam resembles air in appearance, being colorless and transparent.

When the temperature of the water reaches the boiling point, it remains constant until the entire pound of water is evaporated. The quantity of heat that is supplied during this period of change of state is called the **latent heat of evaporation.**

After the entire pound of water has been converted into steam, the further addition of heat will cause an increase in temperature above the boiling point, and the steam will become **superheated.**

The changes occurring during the generation of steam may be illustrated graphically as in Fig. 32. The line AB represents the change in the heat of the liquid with respect to temperature.

BC represents by a horizontal line the latent heat of evaporation; and line CD shows the increase in heat content of the steam with respect to temperature as it becomes superheated to some temperature above the boiling point. It should be observed that the horizontal axis of the graph represents the heat added in Btu, and the vertical axis represents observed temperature. Thus any point along the graph $ABCD$ shows both the amount of heat present in the steam at that point and the Fahrenheit temperature.

71. Dry and Saturated Steam.—*When steam exists at the temperature of evaporation corresponding to the pressure to which it is*

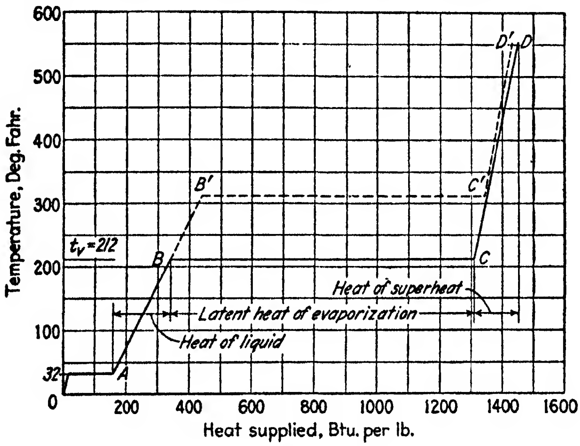


FIG. 32.—Temperature-total heat diagram for the generation of one pound of steam.

subjected, it is called saturated steam. In the process of generating steam, tiny particles of moisture are usually carried into the steam space with the vapor. The steam is said to be saturated when the steam space is filled with vapor at a temperature corresponding to the evaporation temperature for that pressure. If free moisture is also present the steam is called "wet saturated," but if the vapor alone is present it is called "dry saturated." Thus saturated steam may be wet or dry, depending on the conditions accompanying evaporation.

A pound of steam existing at evaporation temperature is **dry and saturated** if all the water from which it is made has been evaporated.

72. Steam Tables.—Table V gives the properties of dry and saturated steam as determined by J. H. Keenan, of Stevens

Table V

PROPERTIES OF DRY AND SATURATED STEAM *

Abs. Press. Lb/Sq In.	Temp. Deg Fahr	Specific Volume			Total Heat			Entropy			Abs. Press. Lb/Sq In.
		Sat. Liquid	Evap.	Sat. Vapor	Sat. Liquid	Evap.	Sat. Vapor	Sat. Liquid	Evap.	Sat. Vapor	
p	t	σ		v	h	L	H	θ	L/T	ϕ	p
½″ Hg	58.83	0.01603	1256.9	1256.9	26.88	1058.8	1085.7	0.0533	2.0422	2.0955	½″ Hg
¾″ Hg	70.44	0.01605	856.5	856.5	38.47	1052.5	1091.0	0.0754	1.9856	2.0609	¾″ Hg
1″ Hg	79.06	0.01607	652.7	652.7	47.06	1047.8	1094.9	0.0914	1.9451	2.0365	1″ Hg
1½″ Hg	91.75	0.01610	445.3	445.3	59.72	1040.8	1100.6	0.1147	1.8877	2.0024	1½″ Hg
2″ Hg	101.17	0.01613	339.5	339.5	69.10	1035.7	1104.8	0.1316	1.8468	1.9784	2″ Hg
2½″ Hg	108.73	0.01616	275.2	275.2	76.63	1031.5	1108.1	0.1450	1.8148	1.9598	2½″ Hg
3″ Hg	115.08	0.01618	231.8	231.8	82.96	1027.9	1110.8	0.1561	1.7885	1.9446	3″ Hg
1	101.76	0.01614	333.8	333.9	69.69	1035.3	1105.0	0.1326	1.8442	1.9769	1
5	162.25	0.01641	73.59	73.61	130.10	1000.4	1130.6	0.2348	1.6088	1.8435	5
10	193.21	0.01658	38.44	38.45	161.13	981.8	1143 0	0.2834	1.5040	1.7874	10
14.696	212.00	0.01670	26.80	26.82	180.00	970.2	1150.2	0.3119	1.4446	1.7564	14.696
15	213.03	0.01671	26.29	26.31	181.04	969.6	1150.6	0.3134	1.4414	1.7548	15
20	227.96	0.01682	20.078	20.095	196.09	959.9	1156.0	0.3356	1.3960	1.7317	20
30	250.34	0.01698	13.728	13.745	218.73	945.0	1163.7	0.3680	1.3310	1.6990	30
40	267.24	0.01712	10.480	10 497	235.93	933.3	1169.2	0.3919	1.2840	1.6759	40
50	281.01	0.01724	8.496	8.514	249.98	923.5	1173.5	0.4111	1.2469	1.6580	50

60	292.71	0.01735	7.155	7.172	261.98	915.0	1177.0	0.4271	1.2162	1.6434	**60**
70	302.92	0.01744	6.186	6.203	272.49	907.4	1179.9	0.4410	1.1900	1.6310	**70**
80	312.03	0.01754	5.452	5.470	281.90	900.5	1182.4	0.4532	1.1670	1.6202	**80**
90	320.27	0.01763	4.874	4.892	290.45	894.2	1184.6	0.4642	1.1465	1.6107	**90**
100	327.83	0.01771	4.408	4.426	298.33	888.2	1186.6	0.4742	1.1280	1.6022	**100**
110	334.79	0.01779	4.026	4.044	305.61	882.7	1188.3	0.4834	1.1111	1.5944	**110**
120	341.26	0.01786	3.707	3.725	312.37	877.4	1189.8	0.4918	1.0956	1.5874	**120**
130	347.31	0.01794	3.433	3.451	318.73	872.4	1191.2	0.4996	1.0812	1.5808	**130**
140	353.03	0.01801	3.198	3.216	324.74	867.7	1192.4	0.5070	1.0677	1.5747	**140**
150	358.43	0.01808	2.992	3.010	330.44	863.1	1193.5	0.5140	1.0550	1.5690	**150**
160	363.55	0.01814	2.812	2.830	335.86	858.7	1194.5	0.5205	1.0431	1.5636	**160**
170	368.42	0.01821	2.653	2.671	341.03	854.4	1195.4	0.5268	1.0318	1.5586	**170**
180	373.08	0.01827	2.511	2.529	345.99	850.3	1196.3	0.5327	1.0211	1.5538	**180**
190	377.55	0.01833	2.383	2.401	350.77	846.3	1197.0	0.5384	1.0109	1.5493	**190**
200	381.82	0.01839	2.267	2.285	355.33	842.4	1197.8	0.5438	1.0012	1.5450	**200**
210	385.93	0.01844	2.162	2.180	359.76	838.6	1198.4	0.5491	0.9918	1.5409	**210**
220	389.89	0.01850	2.066	2.084	364.02	835.0	1199.0	0.5540	0.9829	1.5369	**220**
230	393.70	0.01856	1.9778	1.9964	368.14	831.4	1199.6	0.5588	0.9743	1.5332	**230**
240	397.40	0.01861	1.8970	1.9156	372.13	827.9	1200.1	0.5635	0.9661	1.5295	**240**
250	400.97	0.01867	1.8223	1.8410	376.02	824.5	1200.5	0.5680	0.9581	1.5261	**250**
260	404.43	0.01872	1.7536	1.7723	379.78	821.2	1201.0	0.5723	0.9504	1.5227	**260**
270	407.79	0.01877	1.6895	1.7083	383.44	818.0	1201.4	0.5765	0.9430	1.5194	**270**
280	411.06	0.01882	1.6302	1.6490	387.02	814.7	1201.8	0.5805	0.9357	1.5163	**280**
290	414.24	0.01887	1.5745	1.5934	390.50	811.6	1202.1	0.5845	0.9287	1.5132	**290**

* Adapted from "Steam Tables" by The Superheater Company.

TABLE V—*Continued*

Abs. Press. Lb/Sq In.	Temp. Deg Fahr	Specific Volume			Total Heat			Entropy			Abs. Press. Lb/Sq In.
		Sat. Liquid	Evap.	Sat. Vapor	Sat. Liquid	Evap.	Sat. Vapor	Sat. Liquid	Evap.	Sat. Vapor	
p	t	σ		v	h	L	H	θ	L/T	ϕ	p
300	417.33	0.01892	1.5225	1.5414	393.90	808.5	1202.4	0.5883	0.9220	1.5102	**300**
350	431.71	0.0191	1.3054	1.3245	409.81	793.7	1203.6	0.6061	0.8905	1.4966	**350**
400	444.58	0.0194	1.1407	1.1601	424.2	779.8	1204.1	0.6218	0.8625	1.4843	**400**
450	456.27	0.0196	1.0107	1.0303	437.4	766.7	1204.1	0.6361	0.8371	1.4732	**450**
500	466.99	0.0198	0.9063	0.9261	449.7	754.0	1203.7	0.6493	0.8137	1.4630	**500**
550	476.91	0.0200	0.8202	0.8402	461.3	741.7	1203.0	0 6616	0.7920	1.4536	**550**
600	486.17	0.0202	0.7475	0.7677	472.3	729.8	1202.1	0.6731	0.7716	1.4447	**600**
650	494.86	0.0204	0.6856	0.7060	482.9	718.2	1201.1	0.6840	0.7524	1.4364	**650**
700	503.04	0.0206	0.6321	0.6527	492.9	706.8	1199.7	0.6943	0.7342	1.4285	**700**
750	510.80	0.0208	0.5855	0.6063	502.5	695.7	1198.2	0.7042	0.7169	1.4211	**750**
800	518.18	0.0209	0.5444	0.5653	511.8	684.9	1196.7	0.7135	0.7004	1.4139	**800**
850	525.21	0.0212	0.5080	0.5292	520.8	674.2	1195.0	0.7225	0.6846	1.4071	**850**
900	531.95	0.0213	0.4756	0.4969	529.5	663.8	1193.3	0.7311	0.6694	1.4005	**900**
950	538.40	0.0216	0.4464	0.4680	537.9	653.5	1191.4	0.7394	0.6548	1.3942	**950**
1000	544.58	0.0217	0.4202	0.4419	546.0	643.5	1189.6	0.7473	0.6408	1.3881	**1000**
1050	550.53	0.0219	0.3960	0.4179	554.0	633.6	1187.6	0.7550	0.6273	1.3822	**1050**
1100	556.28	0.0222	0.3738	0.3960	561.7	623.9	1185.6	0.7624	0.6141	1.3765	**1100**
1150	561.81	0.0224	0.3540	0.3764	569.2	614.3	1183.5	0.7695	0.6014	1.3709	**1150**
1200	567.14	0.0226	0.3356	0.3582	576.5	604.9	1181.4	0.7764	0.5891	1.3656	**1200**

1250	572.30	0.0228	0.3187	0.3415	583.6	595.6	1179.2	0.7831	0.5772	1.3603	**1250**
1300	577.32	0.0230	0.3029	0.3259	590.6	586.3	1177.0	0.7897	0.5654	1.3552	**1300**
1350	582.21	0.0232	0.2884	0.3116	597.5	577.2	1174.7	0.7962	0.5540	1.3501	**1350**
1400	586.96	0.0235	0.2748	0.2983	604.3	568.1	1172.4	0.8024	0.5428	1.3452	**1400**
1450	591.58	0.0237	0.2621	0.2858	611.0	559.1	1170.0	0.8086	0.5318	1.3404	**1450**
1500	596.08	0.0239	0.2502	0.2741	617.5	550.2	1167.6	0.8146	0.5212	1.3357	**1500**
1600	604.74	0.0244	0.2284	0.2528	630.2	532.6	1162.7	0.8262	0.5003	1.3265	**1600**
1700	612.98	0.0249	0.2089	0.2338	642.5	515.0	1157.5	0.8373	0.4801	1.3174	**1700**
1800	620.86	0.0254	0.1913	0.2167	654.7	497.2	1151.8	0.8482	0.4601	1.3083	**1800**
1900	628.39	0.0260	0.1754	0.2014	666.8	478.9	1145.7	0.8589	0.4402	1.2990	**1900**
2000	635.6	0.0265	0.1610	0.1875	679.0	460.0	1139.0	0.8696	0.4200	1.2896	**2000**
2100	642.6	0.0271	0.1473	0.1744	691.3	440.4	1131.7	0.8804	0.3996	1.2800	**2100**
2200	649.2	0.0277	0.1346	0.1623	703.7	420.0	1123.8	0.8912	0.3788	1.2700	**2200**
2300	655.7	0.0284	0.1226	0.1510	716.4	398.7	1115.2	0 9021	0.3575	1.2596	**2300**
2400	661.9	0.0292	0.1112	0.1404	729.4	376.4	1105.8	0.9133	0.3356	1.2488	**2400**
2500	668.0	0.0301	0 1002	0.1303	742.8	352.8	1095.6	0.9247	0 3129	1.2375	**2500**
2600	673.8	0.0310	0.0895	0.1205	756.7	327.8	1084 5	0.9364	0.2892	1.2257	**2600**
2700	679.5	0.0321	0.0790	0.1111	771.2	301.2	1072.4	0.9487	0.2644	1.2131	**2700**
2800	684.9	0.0333	0.0688	0.1021	786.7	272 3	1058.9	0 9618	0.2379	1.1996	**2800**
2900	690.2	0.0348	0.0585	0.0933	803.6	240.0	1043.7	0.9760	0.2088	1.1847	**2900**
3000	695.2	0.0367	0.0477	0.0844	823.1	202.5	1025.6	0.9922	0.1754	1.1676	**3000**
3100	700.2	0.0395	0.0348	0.0743	847.2	155.0	1002.2	1.0126	0.1336	1.1462	**3100**
3200	704.9	0.0459	0.0142	0.0601	887.0	75.9	962.9	1.0461	0.0651	1.1112	**3200**
3226†	706.1	0.0522	0	0.0522	925.0	0	925.0	1.0785	0	1.0785	**3226**

† Critical pressure.

Institute of Technology. The following considerations should be clearly understood before attempting to use any of the values listed in this table.

1. All quantities of heat are measured above a temperature of 32 deg fahr, and are expressed in Btu for one pound.

2. All pressures are expressed as absolute pressures in pounds per square inch when above atmospheric pressure; and in pounds per square inch absolute and inches of mercury when below atmospheric pressure.

The following symbols are employed to designate the individual properties as tabulated in Table V:

p = steam pressure, lb per sq in. abs.
t_v = evaporation temperature, deg fahr.
v = specific volume of dry steam, cu ft per lb.
$1/v$ = density of dry steam, lb per cu ft.
h = heat of liquid, Btu per lb.
L = latent heat of evaporation, Btu per lb.
H = total heat of steam, Btu per lb (enthalpy).
θ = entropy of liquid.
L/T = entropy of evaporation.
ϕ = entropy of steam.
σ = volume of one pound of water, cu ft.

73. Heat of the Liquid.—The heat of the liquid, *h*, is the quantity of heat required to raise the temperature of one pound of water from 32 deg fahr to the boiling point. The heat of the liquid for any particular pressure may be calculated as:

$$h = S_p(t_v - 32) \qquad (22)$$

in which

S_p = average specific heat at constant pressure of the water over the temperature range from 32 deg fahr to t_v deg fahr.

t_v = evaporation temperature corresponding to the pressure, deg fahr.

In most cases, steam is not formed by starting with water at 32 deg fahr; usually the initial water temperature is considerably higher than this. When the initial temperature of the water is above 32 deg fahr, the quantity of heat required to bring the

water to the boiling point equals $h - h_1$, in which h = heat of liquid at absolute boiler pressure as obtained from the steam tables, and h_1 = quantity of heat above 32 deg fahr present in one pound of the initial water. The value of h_1 may be taken as = (temperature at which water is supplied to boiler −32), since the specific heat of water is approximately unity.

74. Latent Heat of Evaporation.—The latent heat of evaporation, L, is the quantity of heat required to convert one pound of water at the boiling point into dry steam. It will be noticed from a study of the steam tables that this quantity varies considerably with the pressure, becoming smaller as the pressure increases.

Latent heat is essentially stored heat which is returned or given up when the steam condenses back into water. This fact should be thoroughly appreciated by the student, since it is of great importance in the operation of many pieces of apparatus using steam.

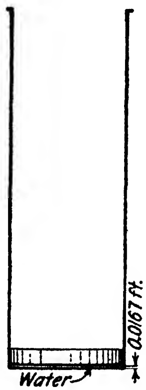


FIG. 33.—Volume occupied by one pound of water at atmospheric pressure.

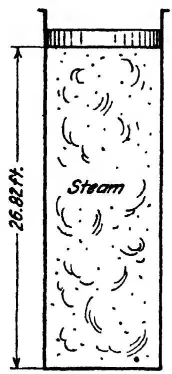


FIG. 34.—Volume occupied by one pound of dry steam at atmospheric pressure.

75. Internal and External Latent Heat.—Fig. 33 represents a cylinder of indefinite length, having a base area of one square foot (144 sq in.), and fitted with a weightless and frictionless piston. Let us assume that this cylinder contains one pound of water at 32 deg fahr under the piston. This amount of water would occupy $1/62.42 = 0.0167$* cu ft, and since the area of the base is one square foot, the water would stand 0.0167 ft high in the cylinder. As the upper end of the cylinder is open, there would be a pressure of 14.7 lb per sq in. on the piston top due to the weight of the atmosphere. This amounts to a total downward force of $14.7 \times 144 = 2117$ lb which must be overcome before the piston can ascend.

Now suppose that heat is applied to the water. The temperature will rise to 212 deg fahr after 180 Btu have been supplied, but

* This value may also be obtained from column 3 of the steam tables given on page 86.

the piston will remain practically stationary. However, as more heat is added, the water gradually changes into steam, and the piston gradually ascends to make room for the steam, since the one pound of steam will require 26.82* cu ft at atmospheric pressure. Thus when all the water has been converted into steam the piston will stand 26.82 ft above the bottom of the cylinder, as shown in Fig. 34. In doing this, the steam has expanded against a total force of 2117 lb and has consequently done 2117(26.82 − 0.017) = 56,714 ft-lb of work. Since 1 Btu = 778 ft-lb, the heat equivalent of the work done is 56,714 ÷ 778 = 72.9 Btu. We know from reference to the steam tables that it requires 970.2 Btu to convert one pound of water at 212 deg fahr into dry steam at that temperature. Since only 72.9 Btu are required to expand the one pound of steam against the external pressure, the difference, or 970.2 − 72.9 = 897.3 Btu, must represent the amount of heat required to increase the rate of vibration of the molecules, i.e., to produce the change of state.

The total quantity of heat imparted to the water in this case may be summarized as follows:

(1) Heat required to raise the temperature of the water from 32 deg fahr to 212 deg fahr (heat of the liquid)	180 Btu.
(2) Heat required to expand the steam against external resistance (external latent heat)	72.9 Btu.
(3) Heat required to increase the internal heat content of the steam (internal latent heat)	897.3 Btu.
Total heat content above 32 deg fahr of one pound of dry and saturated steam	1150.2 Btu.

From the foregoing analysis it will be seen that the latent heat of evaporation may be said to be made up of two parts: (1) the **internal latent heat** and (2) the **external latent heat.**

76. Total Heat per Pound of Dry Steam (Enthalpy).—The **total heat** content of one pound of dry and saturated steam is the amount of heat necessary to convert one pound of water at 32 deg fahr into dry and saturated steam. This is equal to the sum of the heat of the liquid and the latent heat of evaporation at the pressure at which the change takes place. This may be expressed as follows:

$$H = h + L \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

* This value may also be obtained from column 5 of the steam tables given on page 86.

in which

H = total heat of one pound of dry and saturated steam, Btu.

h = heat of the liquid, Btu per lb.

L = total latent heat of evaporation, Btu per lb.

Example 1.

What quantity of heat is required to raise one pound of water from 32 deg fahr to dry and saturated steam at 80 lb per sq in. abs?

Solution.

$$H = h + L$$
$$H = 281.9 + 900.5 = 1182.4 \text{ Btu.}$$

The values of h and L are taken directly from the steam table.

Example 2.

Determine the quantity of heat required to convert 1 lb of water at 72 deg fahr into dry and saturated steam at 100 lb per sq in. abs.

Solution.

Heat of liquid, h, above 32 deg fahr
= 298.3 Btu (from steam table).

Initial heat content of water above 32 deg fahr
= 72 − 32 = 40 Btu.

Heat required to raise water to boiling point
= 298.3 − 40 = 258.3 Btu.

Latent heat of evaporation from steam table
= 888.2 Btu.

Total quantity of heat supplied to water
= 258.3 + 888.2 = 1146.5 Btu.

Example 3.

A boiler evaporates 3000 lb of water per hr into dry and saturated steam at a gage pressure of 95.3 lb per sq in. If the water is fed to the boiler at 120 deg fahr, what quantity of heat is delivered to the water per hour? Barometer reading, 29.92 in. of mercury.

Solution.

Absolute steam pressure = 95.3 + (29.92 × 0.491)
= 110.0 lb. per sq in.

Heat of liquid at 110 lb per sq in.
= 305.6 Btu per lb (from steam tables).

Initial heat content of water at 120 deg fahr
= 120 − 32 = 88 Btu per lb.

Latent heat of evaporation at 110 lb per sq in.
= 882.7 Btu. per lb.

Total heat supplied per pound of steam

$$= (305.6 - 88) + 882.7 = 1100.3 \text{ Btu.}$$

Total heat supplied per hour

$$= 1100.3 \times 3000 = 3{,}300{,}900 \text{ Btu.}$$

77. Wet Steam.—Saturated steam which carries entrained moisture is called **wet steam.** This moisture is finely divided and remains suspended in the steam as a mist or fog. Steam in this condition is composed partly of suspended water particles and partly of steam.

Before a given weight of water can be converted into steam at a certain pressure, the entire weight of the water must first be heated to the evaporation temperature corresponding to the pressure. Then if x parts by weight are made into steam, the heat xL must be added, making the total heat to be added to the water $h + xL$. Hence

$$H_w = h + xL \quad \ldots \ldots \ldots \quad (24)$$

in which

H_w = total heat of a pound of mixture of water and steam above 32 deg fahr, Btu.
h = heat of liquid, Btu per lb.
x = quality of steam.
L = latent heat of evaporation, Btu per lb.

The term **quality** is applied to the portion of dry steam contained in a pound of wet steam, and the term **moisture** refers to the proportion of the water that remains unevaporated. The quality, x, and the moisture, m, are expressed as percentages of the total weight. Thus steam having a quality of 97 percent is a mixture of 97 parts by weight of steam and 3 parts by weight of water. The sum of the quality and the moisture contents equals 100 percent.

Example 1.

A boiler contains steam of 98 percent quality at a pressure of 120 lb per sq in. abs. What is the heat content per pound of steam?

Solution.

$$H_w = h + xL$$

$$H_w = 312.4 + 0.98 \times 877.4 = 1182.0 \text{ Btu per lb.}$$

78. Superheated Steam.—*Steam having a temperature higher than the evaporation temperature corresponding to the pressure at*

which it exists is called superheated steam. Steam is superheated by adding heat to it after the steam is removed from contact with water. This is usually done by drawing saturated steam from the boiler and passing it through a series of tubes located in the path of the furnace gases.

The amount by which the steam temperature exceeds the evaporation temperature corresponding to the steam pressure is called the *number of degrees of superheat.* The number of degrees of superheat shows the rise in temperature above saturation conditions.

The total heat of one pound of superheated steam is equal to the total heat of one pound of saturated steam plus the heat required to raise the temperature of the one pound of steam from that of evaporation to its final temperature of superheat. This may be expressed as follows:

$$H_s = H + S_p(t_s - t_v) \quad . \quad . \quad . \quad . \quad . \quad (25)$$

in which

H_s = total heat content of one pound of superheated steam, Btu.

S_p = mean specific heat of superheated steam at the temperature and pressure of superheat, Btu per lb per deg fahr.

t_s = temperature of superheated steam, deg fahr.

t_v = temperature of evaporation, deg fahr.

The value of the specific heat of superheated steam, S_p, is not constant, but varies with the pressure and temperature. An average value for the specific heat for any particular condition of pressure and superheat may be obtained from the curves in Fig. 35.

Example 1.

Compute the quantity of heat required to convert 1 lb of water at 32 deg fahr into steam at 50 lb per sq in. abs pressure with 100 deg fahr of superheat.

Solution.

$H_s = H + S_p(t_s - t_v).$

$H_s = 1173.5 + 0.503 \times 100 = 1223.8$ Btu per lb.

79. Specific Volume and Density of Dry Saturated Steam.— The specific volume, v, of dry saturated steam is the volume in cubic feet occupied by one pound of dry saturated steam. The

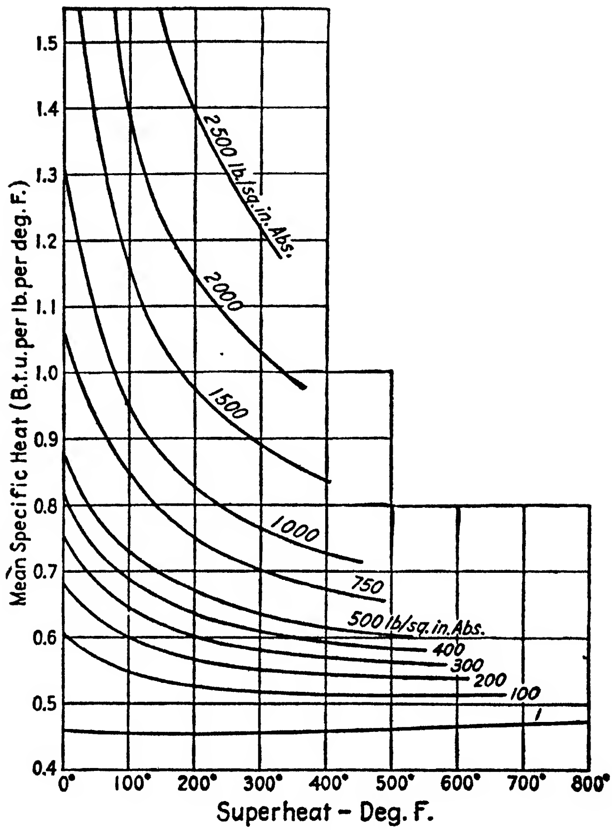


FIG. 35.—Mean specific heat of superheated steam.

(Computed by J. H. Keenan, from Keenan, Steam Tables and Mollier Diagram).

specific volume varies with the pressure, becoming very small at the higher pressures.

The specific density, d, of dry saturated steam is the weight of the steam in pounds per cubic foot. The density is the reciprocal of the specific volume, or:

$$d = \frac{1}{v} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (26)$$

The density varies directly with the pressure, becoming larger as the pressure is increased.

SUMMARY OF CHAPTER IV

If heat is applied to any solid substance it will pass through three successive states, namely: SOLID, LIQUID, and GASEOUS.

FUSION is the process by which a substance is changed from the solid to the liquid state by the addition of heat to the solid material. The temperature at which this change occurs is known as the MELTING POINT of the solid; and the amount of heat required to perform this transition for one pound of the solid without a change in temperature is known as the LATENT HEAT OF FUSION of the substance. For example, 144 Btu are required to convert one pound of ice at 32 deg fahr to one pound of water at 32 deg fahr.

The melting temperature of an alloy is affected by the percentage of the alloyed constituents present. The lowest temperature at which a liquid mixture of two alloyed substances can exist is known as the EUTECTIC TEMPERATURE; and the percentage mixture that produces this effect is the EUTECTIC MIXTURE.

EVAPORATION is the process by which a liquid is converted into a gas by the addition of heat to the liquid. The temperature at which this change occurs is known as the BOILING POINT of the liquid; and the amount of heat required to complete this change for one pound of liquid, at constant temperature, is known as the LATENT HEAT OF EVAPORATION. For example, 970.2 Btu are required to convert one pound of water at 212 deg fahr into one pound of steam at 212 deg fahr at atmospheric pressure.

The temperature of evaporation of a substance depends entirely upon the pressure exerted upon the surface of the substance. If the pressure is increased, the boiling temperature is increased, and vice versa.

The STEAM TABLES represent a compilation of the properties of steam for various conditions of pressure and temperature. They are purely experimental in origin, having been compiled in tabular form by scientists after carrying on many laboratory experiments to ascertain the various physical properties.

In the steam tables, the HEAT OF THE LIQUID, h, is the amount of heat required to raise the temperature of one pound of water from 32 deg fahr to the boiling point.

The LATENT HEAT OF EVAPORATION, L, is the quantity of heat required to completely evaporate one pound of water into steam under conditions of constant pressure.

The latent heat of evaporation may be divided into two parts, namely:

1. The heat required to expand the one pound of steam against the external pressure, known as the EXTERNAL LATENT HEAT.
2. Heat used in increasing the rate of vibration of the molecules of steam, known as the INTERNAL LATENT HEAT.

The total heat per pound of dry steam, $H = h + L$.

The total heat per pound of wet steam, $H_w = h + xL$, in which x = the quality of the steam.

The total heat per pound of superheated steam, $H_s = H + S_p(t_s - t_v)$; in which S_p is the specific heat of superheated steam.

SUPERHEATED STEAM is steam at a higher temperature than the evaporation temperature for the pressure at which the steam exists. The amount by which the steam temperature exceeds the evaporation temperature is known as the number of DEGREES OF SUPERHEAT of the steam.

REVIEW PROBLEMS ON CHAPTER IV

1. Draw total heat-temperature diagrams for the following problems. Give the numerical values of the items listed below, and place these values in their proper location on the total heat-temperature diagram.

1. t_f = temperature of feedwater, deg fahr.
2. t_v = evaporation temperature, deg fahr.
3. t_s = temperature of superheated steam, deg fahr.
4. h = heat of liquid above 32 deg fahr, Btu per lb.
5. h_1 = heat of liquid above 32 deg fahr contained by feedwater, Btu per lb.
6. L = latent heat of evaporation, Btu per lb.
7. x = quality of steam, percent.
8. xL = percent of latent heat supplied, Btu per lb.
9. S = heat of superheat, Btu per lb.

(*a*) One pound of water at 32 deg fahr converted into dry and saturated steam at 100 lb per sq in. abs.

(*b*) One pound of water at 182 deg fahr converted into dry and saturated steam at a pressure of 200 lb per sq in. abs.

(*c*) One pound of water at 202 deg fahr converted into steam of 98 percent quality at a pressure of 150 lb per sq in. abs.

(*d*) One pound of water at 212 deg fahr converted into steam of 100 deg superheat at a pressure of 250 lb per sq in. abs.

2. If a boiler evaporates 4500 lb of water per hour from a feedwater temperature of 192 deg fahr into steam at 135.3 lb per sq in. gage with a temperature of 458.4 deg fahr, how many Btu per hour are supplied to the water in the boiler?

3. Draw the total heat-temperature diagram for problem 2.

4. If the boiler in problem 2 burns coal with a heating value of 14,250 Btu per lb, how many pounds of coal per day of 24 hr will be required if the combined efficiency of the boiler, furnace, and grate is 60 percent?

CHAPTER V

STEAM CALORIMETERS

80. Types of Steam Calorimeters.—The steam calorimeter is used to determine the percentage of moisture present in a pound of wet steam. The two most popular types of steam calorimeters in general use are: (1) the throttling calorimeter, and (2) the separating calorimeter. These types will be discussed in the order of their importance.

81. The Throttling Calorimeter.—Because of its high degree of accuracy and low cost of construction, the throttling calorimeter

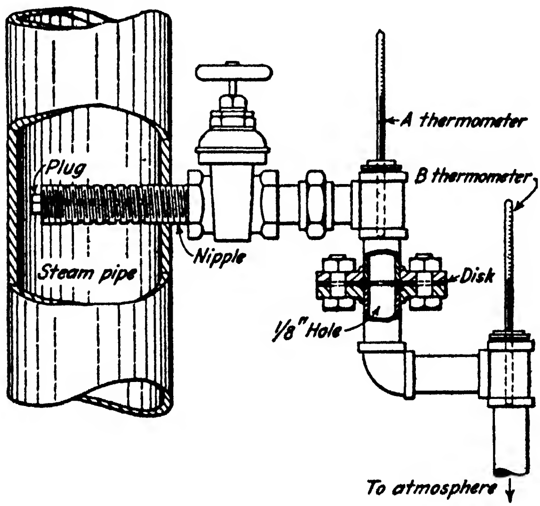


FIG. 36.—A.S.M.E. type of throttling calorimeter.

is the most frequently used instrument for determining the percentage of moisture in wet steam. Fig. 36 is representative of the type of throttling calorimeter recommended by the American Society of Mechanical Engineers. This is made of pipe fittings and consists essentially of a means of conducting a sample of steam from the steam main through a $\frac{1}{8}$-in. hole in a small disk which is

held between two flanges inside the calorimeter. This hole is known as an **orifice.**

The sample of steam to be tested is taken from the steam main through a **sampling tube** which extends into the steam main. The sampling tube is perforated in such a manner as to select a fair sample of the steam flowing through the main and pass it on into the calorimeter. Two Fahrenheit thermometers, *A* and *B*, are employed to indicate the temperature of the steam before and after it passes through the $\frac{1}{8}$-in. hole in the disk. A steam pressure gage (not shown) is attached to the steam main near the calorimeter for obtaining the pressure of the steam as it enters the calorimeter.

It is essential that the entire calorimeter, as well as the connecting pipe, be well insulated to reduce the heat losses to a minimum. A material well suited for this purpose is hair felt. The hair felt is packed around the calorimeter and piping in such a manner as to provide a thickness of insulation of about one inch.

82. Operation of the Throttling Calorimeter.—When the globe valve of the calorimeter is opened, steam from the steam main passes through the sampling tube into the calorimeter where its temperature is indicated by the thermometer *A*. It next passes through the $\frac{1}{8}$-in. hole in the disk and around the thermometer *B* and is then discharged to the atmosphere. Before any readings of temperature are taken, the calorimeter should be operated for a sufficient period of time to allow conditions to become stable. Particular care should be exercised to assure a steady reading of thermometer *B* before any moisture determinations are made.

When steam passes through an orifice from a higher to a lower pressure, as in the case of the throttling calorimeter, no external work has been done in overcoming a resistance.* Hence, assuming no loss by radiation, the quantity of heat contained in the steam after it has passed through the orifice will be the same as before it passed through the orifice. If, for example, the pressure of the steam in the main is 150.3 lb per sq in. gage, and the pressure of the atmosphere is 14.7 lb per sq in. abs, the total heat in a pound of dry steam in the main would be, from the steam tables, 1194.6 Btu. However, when this pound of steam is passed through the orifice, its pressure is reduced to that of the atmos-

* External work is the work done by a vapor in expanding against any pressure greater than that of the atmosphere.

phere, but its total heat would remain the same as before. Now, by consulting the steam tables again we observe that the total heat in a pound of *dry* steam at atmospheric pressure is 1150.2 Btu. Thus, if the steam after passing the orifice contains 1194.6 Btu per lb, whereas dry steam at atmospheric pressure contains only 1150.2 Btu per lb, then the steam on the atmospheric side of the orifice must be superheated, 1194.6 − 1150.2 = 44.4 Btu being the amount of energy available to produce superheat.

Assuming the specific heat of superheated steam to be 0.47, each pound passing through the orifice will be superheated 44.4 ÷ 0.47 = 94.5 deg fahr.

If, however, the steam in the main had contained one percent of moisture, its total heat would have been less per pound than if it were dry. Since the latent heat of steam at 150.3 lb per sq in. gage pressure is 858.3 Btu, it follows that the one percent of moisture would have required 8.58 Btu to evaporate it, leaving only 44.4 − 8.58 = 35.82 Btu available for superheating; hence, the superheat would be 35.82/0.47 = 76.3 deg fahr, as against 94.5 deg for dry steam. In a similar manner, the degree of superheat for other percentages of moisture may be determined. It is to be noticed that the greater the percentage of moisture contained in the steam at the higher pressure, the smaller the degree of superheat after passing the orifice.

The method of computing the percentage of moisture in the steam supplied to the calorimeter depends on the fact that: *The total heat contained by one pound of wet steam before passing the orifice equals the total heat contained by one pound of superheated steam after passing the orifice.*

Let H_w = total heat per pound of wet steam at absolute steam-main pressure before passing the orifice.

h = heat of liquid per pound of steam at absolute steam-main pressure.

L = latent heat per pound of steam at absolute steam-main pressure.

H = total heat per pound of dry steam at atmospheric pressure.

t_v = temperature of saturated steam at atmospheric pressure.

t_s = temperature of superheated steam after passing through orifice.

0.47 = specific heat of superheated steam at atmospheric pressure.

x = quality of wet steam, or the proportionate part of dry steam contained in a pound of wet steam.

H_s = total heat per pound of superheated steam after passing the orifice.

The total heat per pound of wet steam, H_w, before passing the orifice is equal to $h + xL$.

The total heat per pound of superheated steam, H_s, after passing the orifice is equal to $H + 0.47(t_s - t_v)$

But $H_w = H_s$. Therefore

$$h + xL = H + 0.47(t_s - t_v) \quad . \quad . \quad . \quad . \quad (27)$$

Transposing this equation in a form to obtain the value of the quality, x, we have:

$$x = \frac{H + 0.47(t_s - t_v) - h}{L} \quad . \quad . \quad . \quad . \quad (28)$$

The proportionate part of moisture, m, contained in a pound of wet steam may be found by subtracting the percent quality, as obtained by the foregoing equation, from 100 percent.

Example 1.

Steam is supplied to a throttling calorimeter at a pressure of 110 lb per sq in. gage; calorimeter exhausts to atmosphere; temperature on atmospheric side of orifice is 260 deg fahr; barometer, 30.55 in. of mercury. Determine the quality of the steam.

Solution.

Atmospheric pressure = 30.55 × 0.491 = 15.00 lb per sq in.

Absolute pressure of steam as supplied to calorimeter = 110 + 15 = 125 lb per sq in.

Temperature corresponding to atmospheric pressure (t_v) = 213.0 deg fahr.

Temperature in calorimeter after orifice (t_s) = 260 deg fahr.

Heat of liquid, h, at 125 lb per sq in. abs pressure = 315.6 Btu.

Latent heat, L, at 125 lb per sq in. abs, pressure = 874.9 Btu.

Total heat per pound of dry steam at 15 lb per sq in. abs pressure = 1150.6 Btu.

$$x = \frac{H + 0.47(t_s - t_v) - h}{L}$$

$$x = \frac{1150.6 + 0.47(260 - 213) - 315.6}{874.9} = 0.98$$

Thus the quality of the steam in the main is 98.0 percent and the moisture would be 100.0 − 98.0 = 2.0 percent.

83. Thermometer Error.—The largest single error encountered in the use of a throttling calorimeter results from the fact that the stem of the thermometer is not heated to the same temperature throughout its entire length. With an ordinary mercury thermometer immersed to the 100-deg mark, the error resulting when the thermometer reads 300 deg fahr may be as large as 3 deg, the true temperature being 303 deg fahr instead of 300. The amount of this correction may be calculated by the following equation:

$$\text{Stem correction in degrees} = 0.000085n(t_o - t_s) \quad . \quad (29)$$

in which

t_o = observed temperature, deg fahr.
t_s = mean temperature of emergent stem, deg fahr.
n = number of degrees of mercury column emergent, deg.
0.000085 = difference between coefficient of expansion of mercury and glass, in. per in. per deg fahr. (Consult material in Chapter III.)

To illustrate the method of calculating the stem correction for a mercury thermometer suppose the observed temperature to be 400 deg fahr, and that the thermometer is immersed to the 100-deg mark, leaving 300 deg of the mercury column projecting into the air. Assume the mean temperature of the surrounding air to be 85 deg fahr; then,

$$\text{Stem correction} = 0.000085 \times 300 \times (400 - 85) = 8.03 \text{ deg.}$$

As the stem is at a lower temperature than the bulb, the thermometer will read too low, so that this correction of 8.03 deg must be added to the observed thermometer reading to find the true temperature. Thus, in this case, the true temperature is 400 + 8.03 = 408.3 deg fahr.

84. Limits of Usage.—The limits of moisture within which the throttling calorimeter will work are, at sea level, from 2.88 percent at 50 lb gage pressure to 7.17 percent moisture at 250 lb gage pressure. The student may check these percentages and also determine percentages for other pressures by a computation similar to that in section 82. The limiting value of steam quality is reached when the steam after passing through the orifice contains no superheat, i.e., it is dry and saturated.

85. Other Forms of Throttling Calorimeter.—In the practical operation of the throttling calorimeter shown in Fig. 36, the first thermometer, A, is frequently disregarded and the pressure in the steam main is measured with an accurate steam gage. Many forms of throttling calorimeters are constructed with only the low-pressure thermometer; one of the more common ones is illustrated in Fig. 37. This instrument consists of two concentric metal cylinders screwed into a cap containing a thermometer well in its center. The steam pressure is usually measured by means of a steam gage located in the steam supply pipe leading to the calorimeter. Steam enters the instrument through the orifice, A, and expands to atmospheric pressure, its temperature at this pressure being measured by a thermometer placed in the cup C. Steam is also supplied through the hole B to the annular space between the two concentric jackets. The purpose of this is to surround the calorimeter with a heated jacket in order to reduce radiation losses to a minimum. However, it is still essential that the instrument and all pipes and fittings leading to it should be thoroughly insulated to further reduce radiation losses.

86. The Separating Calorimeter.—The operation of the separating calorimeter depends on the mechanical separation of the entrained moisture from the steam. This separated moisture is collected in a reservoir where its amount is either indicated by a gage glass or drained off and weighed. Fig. 38 is representative of a calorimeter of this type. The gage attached to the side of the calorimeter serves a dual purpose. First, it indicates the pressure in the inner chamber of the instrument; and second, it is so graduated that it also indicates the weight of steam flowing into the calorimeter for a period of ten minutes, this latter scale being graduated by trial.

When the angle valve is opened, steam enters the calorimeter

and impinges against the bottom of a small cup where its direction of flow is reversed. This rapid reversal of flow causes a separation of any entrained water in the steam, the water being deposited against the sides of the separating cup. The water collected in this manner passes through small holes in the sides of the cup and is deposited in the inner chamber below, where its amount may be read on the graduated scale beside the water glass This quantity of separated water, w, may also be drained from the instrument and weighed.

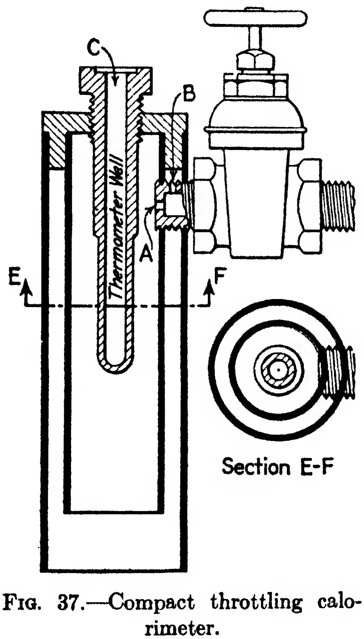


FIG. 37.—Compact throttling calorimeter.

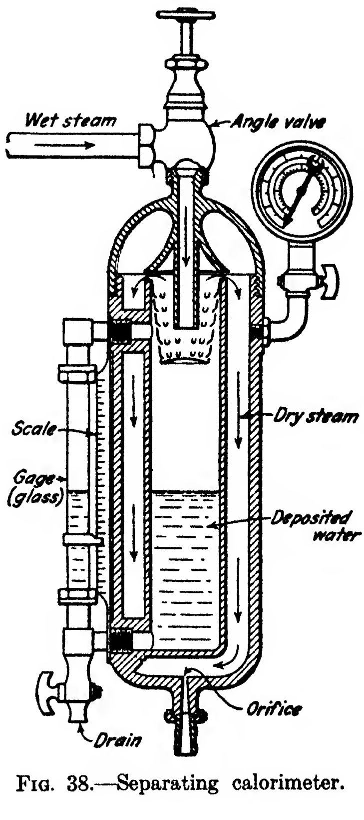


FIG. 38.—Separating calorimeter.

The dry steam leaving the separator cup passes upward to the outer chamber of the instrument, where it flows down to the discharge orifice at the bottom. The amount of dry steam discharged through this orifice during a test can be found by condensing the steam and weighing the condensate. Let us designate this weight of dry steam by the letter W.

Thus the proportion of moisture contained in the steam may be found from the following relation:

$$\text{Moisture} = \frac{\text{Weight of moisture collected}}{\left\{\begin{matrix}\text{Weight of dry steam collected} \\ +\text{Weight of moisture collected}\end{matrix}\right\}}$$

$$\text{Moisture} = \frac{w}{W + w} \quad \ldots\ldots\ldots\ldots \quad (30)$$

The quality of the steam is found by subtracting the percentage of moisture from 100 percent.

Example 1.

A separating calorimeter used to determine the moisture content contained by steam being supplied to a reciprocating steam engine gave the following data: weight of water separated in 10 minutes, 0.20 lb; weight of dry steam exhausted by calorimeter in 10 minutes, 4.80 lb. What was the percentage of moisture and the quality of the steam?

Solution.

$$m = \frac{w}{W + w} = \frac{0.20}{4.80 + 0.20} = 0.04 = 4.0 \text{ percent moisture.}$$

$$\text{Percent quality} = 100 - 4.0 = 96 \text{ percent.}$$

87. Method of Calculating Flow of Steam through Calorimeter Orifice.—The quantity of dry steam discharged from the orifice at the bottom of the separating calorimeter may be calculated by means of Napier's law, which is as follows: *The flow of steam from a higher to a lower pressure is directly proportional to the higher absolute pressure and to the cross-sectional area of the orifice, as long as the lower pressure is less than 58 percent of the higher pressure.*

Expressing this law in the form of an equation we have:

$$W = \frac{Pa}{70} \quad \ldots\ldots\ldots\ldots \quad (31)$$

in which

W = quantity of steam flowing, lb per sec.

P = absolute steam pressure before passing the orifice, lb per sq in.

a = cross-sectional area of orifice, sq in.

Thus the quantity of steam discharged from a separating calorimeter may be calculated by Napier's equation if the size of the orifice and the steam pressure before the orifice are known. However, if this method is to be followed, care should be taken to see that the orifice is free from sediment.

Example 1.

During the operation of a separating calorimeter the following data were taken: pressure in calorimeter before orifice as read by gage, 35.3 lb per sq in.; barometer, 29.92 in. of mercury; area of calorimeter orifice, 0.011 sq in.; weight of moisture shown by water glass gage in 10 min, 0.21 lb. Determine the moisture content of the steam using Napier's equation.

Solution.

Atmospheric pressure $= 29.92 \times 0.491 = 14.7$ lb per sq in.

Absolute pressure before orifice $= 35.3 + 14.7 = 50.0$ lb per sq in.

Weight of dry steam discharged from the calorimeter per second, by Napier's equation:

$$W = \frac{Pa}{70} = \frac{50 \times 0.011}{70} = 0.00786 \text{ lb per sec.}$$

Weight of dry steam discharged per minute $= 0.00786 \times 60 = 0.472$ lb per min.

Weight of dry steam discharged in 10 min $= 0.472 \times 10 = 4.72$ lb.

$$\text{Moisture} = \frac{w}{W + w} = \frac{0.21}{4.72 + 0.21} = 0.0426 \text{ or } 4.26 \text{ percent.}$$

Thus quality $= 100.00 - 4.26 = 95.74$ percent.

88. Specifications for Sampling Nozzle.—The American Society of Mechanical Engineers recommends a sampling nozzle made of ½-in. iron pipe closed at the inner end. The interior portion should be perforated with not less than twenty ⅛-in. holes distributed equally from end to end, and preferably drilled in irregular spiral rows, the first hole being not less than ½ in. from the wall of the steam main.

This sampling nozzle should be located as near as possible to the point from which the steam leaves the boiler, and where there is no chance for moisture to pocket in the pipe. An effective method to prevent such collection of moisture is to locate the

calorimeter sampling nozzle in a vertical steam main. This permits the moisture collected at the sampling nozzle to drop down the steam main instead of going into the calorimeter.

SUMMARY OF CHAPTER V

The STEAM CALORIMETER is an instrument used to determine the percentage of moisture in wet steam. The two principal types of steam calorimeters in common use are: (1) the throttling calorimeter, and (2) the separating calorimeter.

The THROTTLING CALORIMETER selects a sample of steam to be tested and passes it through an orifice where it is expanded to atmospheric pressure. Since there is no loss of heat in this operation, the steam after passing the orifice will contain more heat units per pound than a pound of dry steam at atmospheric pressure; that is, the steam becomes superheated after passing the orifice. The amount by which the steam becomes superheated will depend entirely on the quantity of heat contained in the original steam before it was expanded through the orifice. Now, assuming the original steam to be wet, we arrive at the following statement:

Total heat per pound of wet steam before the orifice
= Total heat per pound of superheated steam after the orifice.

Expressing this in equation form:

$$h + xL = H + 0.47(t_s - t_v)$$

The SEPARATING CALORIMETER, as the name implies, actually separates the moisture from the wet steam and collects this moisture in a chamber where its amount may be determined. The dry steam remaining after the separation process is discharged from the calorimeter through an orifice and condensed and weighed. The percentage of moisture will equal

$$\frac{w}{w + W} \times 100$$

If the area of the discharge orifice of the separating calorimeter is known, it is possible to calculate the weight of the discharged dry steam by means of Napier's equation, which is as follows:

$$W = \frac{Pa}{70}$$

REVIEW PROBLEMS ON CHAPTER V

1. Steam at 100 lb per sq in. abs pressure and 98 percent quality is passed through a throttling calorimeter, the pressure in the calorimeter being 14.7 lb per sq in. abs. What is the temperature of the steam as it leaves the calorimeter?

2. During a test the following data were obtained from a throttling calorimeter: pressure in calorimeter, 14.7 lb per sq in. abs; temperature in calorimeter, 280 deg fahr; pressure in steam main, 185.3 lb per sq in. gage; barometer reading, 29.92 in. of mercury. Determine the percentage of moisture of the steam in the main.

3. Steam at 80.3 lb per sq in. gage is passed through a throttling calorimeter, the temperature after the orifice being 220 deg fahr, and the pressure after the orifice being 14.7 lb per sq in. abs. What was the original quality of the steam?

4. Determine the maximum percentage of moisture that can be measured by a throttling calorimeter when operated at sea level with steam at 300 lb per sq in. abs.

5. Steam is supplied to a throttling calorimeter the low-pressure side of which is connected to a condenser operating at a vacuum of 28.1 in. of mercury. The pressure of the steam in the main is 160 lb per sq in. abs, and the temperature of the steam after leaving the orifice is 255 deg fahr. Determine the initial quality of the steam. Barometer reading, 29.6 in. of mercury.

6. A tank contains 200 lb of water at 70 deg fahr. Steam under a pressure of 400 lb per sq in. abs was admitted to the tank until the temperature became 100 deg fahr. The weight of the water in the tank increased 5 lb owing to the condensation of the steam. Determine the quality of the steam.

7. Determine the number of pounds of steam per hour that will flow through a $\frac{1}{2}$-in. diameter orifice if the steam is supplied to the orifice at a pressure of 120 lb per sq in. abs, and discharged at a pressure of 14.7 lb per sq in. abs.

8. The following data were taken from a separating calorimeter during a 10-min test: weight of water collected, 0.092 lb; area of calorimeter orifice, 0.00362 sq in.; pressure in calorimeter before orifice, 100 lb per sq in. abs. Determine the quality of the steam tested.

9. Steam at 150 lb per sq in. abs is passed through a separating calorimeter. If, during a 30-min run, 13 lb of dry steam leave the instrument and 1.2 lb of water are collected, what is the quality of the steam? What is the area of the calorimeter orifice?

CHAPTER VI

CONDUCTION, CONVECTION, AND RADIATION

89. Transmission of Heat.—If one end of a cold bar of iron is held in a fire we soon feel heat transmitted through the bar to our hand. When heat energy is transferred from one part of a body to another, without an apparent motion of the entire body itself, intervening parts being also heated, the heat is said to be conducted through the body. *Conduction, then, is the process of transferring heat through a substance without any motion of the substance as a whole.* This phenomenon may take place in liquids and gases as well as in solids.

If a person stands in the path of the current of warm air coming from a register, he becomes warmed as a result. The heat contained by the air is carrried from the register to the person, thereby warming him. It is quite evident that this process of transmitting heat is of an entirely different character from that of the transmission of heat through the rod in the foregoing example. When heat is transmitted from one place to another by actual motion of the hot body, as in this case, the heat is said to be *conveyed.* This process of heat transmission is called convection. *Convection is the process of carrying heat from one place to another by actual motion of the hot body.*

If we sit beside a bonfire, we are warmed. We may think at first that this heat is being carried to us by a movement of heated air towards us. But if we analyze this situation, we discover that the air currents move in towards the fire away from us at the base, whence they travel upwards as smoke. Thus it is quite apparent that the air cannot carry the heat to our bodies since its motion is not in our direction. Here we arrive at the hypothesis of a still different method of heat transmission known as radiation. *Radiation is defined as the process of transmitting heat without the aid of any molecular or mass motion*, as, for example, when heat is radiated from the sun to the earth through space containing no known atoms, molecules, or substances.

90. Cause of Heat Flow.—Heat flows from one part of a body to another part only when there is a difference in temperature between the parts, the flow of heat being toward the point of lower temperature. The flow of heat from a point of higher temperature to one of lower temperature may be likened to the flow of water from a position of higher elevation to one of lower elevation. The higher body of water can lose water only by transferring it to a lower level. In a similar way, a body at a given temperature can lose heat only to a body at a lower temperature.

Suppose that two vessels are filled with water to different levels, the vessels being interconnected by a pipe fitted with a valve, as shown in Fig. 39. As soon as this valve is opened, the water will flow out of the vessel of higher level into the vessel of lower level, until a condition of equilibrium is reached where the water is at the same level in both vessels. (See Fig. 40.) When heat flows from a hot to a cold body, the temperature of the hot

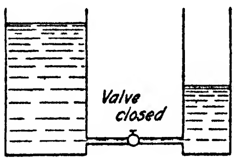


Fig. 39.—Water in disequilibrium.

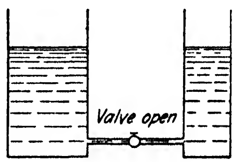


Fig. 40.—Water in equilibrium.

body falls, while the temperature of the cold body rises, until finally both bodies arrive at the same temperature, and the flow of heat ceases. This final condition is referred to as one of **thermal equilibrium.**

If heat is to flow continuously from point A to point B, point A must be maintained at a higher temperature than point B. In order to do this, any heat leaving point A must be immediately replaced by the entrance of an equal quantity of heat. Thus the heat lost from a room must be continuously replaced by an equal quantity of heat from the radiators if the room is to be kept at a constant temperature.

91. Conduction.—As stated in the foregoing section, conduction is the flow of heat through a substance, accompanied by no obvious mass motion of the substance, as, for example, the passage of heat through the walls of a room to the colder air outside. To gain a better understanding of the conditions controlling the

rate of heat transfer by conduction let us assume a set of conditions. Suppose that a rod such as shown in Fig. 41 separates a region of high temperature, t_2, from a region of lower temperature, t_1. A quantity of heat, H, will be conducted through the rod in a given unit of time, let us say one hour. This hourly quantity of heat will depend upon the following considerations:

(1) *The quantity of heat passing through the rod in one hour will depend directly on the difference in temperature between the two ends.* If we think of the rod as a pipe, and heat as a fluid such as water, we may make a convenient analogy here which will help us to form a mental picture of what is happening. A difference in level of the two ends of the pipe will correspond to the difference in temperature. The greater this difference in level, the greater will be the amount of water that flows through the pipe in a given unit of time. In quite the same way, the greater the difference in temperature between the two ends of the rod, the greater will be the amount of heat that flows per hour. Thus, we say that the hourly flow of heat is in direct proportion to the temperature difference; or, expressed mathematically:

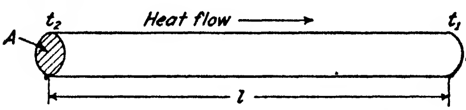


Fig. 41.—Heat flow through a metal rod.

$$H \text{ is proportional to } (t_2 - t_1)$$

(2) *The hourly quantity of heat conducted through the rod will decrease as the length of the rod increases.* In other words, if the original rod is replaced by a new one whose length is twice that of the original rod, it will be found that only one-half the original quantity of heat will flow through it in an hour's time. Here again the conditions are analogous to those in the water pipe. The greater the length the less the flow under a given set of conditions of size of pipe and pressure, since the frictional path of the water is increased. Summing up this quantitative analysis thus far, we have,

$$H \text{ is proportional to } \frac{(t_2 - t_1)}{l}$$

in which l = the length of rod.

(3) *The amount of heat passing through the rod in an hour will also depend directly upon the cross-sectional area, A, of the rod.* In this case, just as in a water pipe, the greater the area of the section through which the flow takes place, the larger the quantity that will flow. Now, again, we have:

$$H \text{ is proportional to } \frac{(t_2 - t_1)A}{l}$$

(4) Finally, *the quantity of heat conducted through the rod in an hour depends greatly upon the kind of material of which the rod is composed.* For example, if the rod were of copper, we would find that the rate of heat flow would be considerably greater than that for a glass rod of the same size. Hence, substances are roughly divided into two classes, namely: (1) good conductors, (2) poor conductors. Substances such as wood, glass, paper, cloth, asbestos, clay, etc., which permit the passage of a small amount of heat through them in a given time, are termed poor conductors.

In our hydrostatic analogy, the quantity of water flowing through a pipe will depend upon the nature, or character, of the inner walls of the pipe. If the inner walls of the pipe are very rough they will offer a greater resistance to the flow of water than if they are smooth. Thus we may say that the passage of water through a pipe is in direct proportion to a factor expressing the difficulty with which the flow of water takes place. In a similar manner, we say that the passage of heat through a rod is in direct proportion to a factor, K, which expresses the difficulty with which the flow of heat takes place. This factor, K, called the *coefficient of heat conductivity,* depends entirely upon the nature, or character, of the material through which the flow of heat is occurring.

The coefficient of heat conductivity merely expresses the quantity of heat in Btu that will pass through a one-inch thickness of the material in an hour when the temperature difference is one degree Fahrenheit and the cross-sectional area is one square foot. This coefficient is different for every kind of material, and may be obtained only by experimental means. The values of K for a few of the more common engineering materials are given in Table VI.

TABLE VI

COEFFICIENT OF HEAT CONDUCTIVITY FOR VARIOUS MATERIALS

(Btu per hr per deg fahr per sq ft per in. thickness)

Material	K	Material	K
Air	0.16	Plaster	8.00
Aluminum	1420.00	Plaster board	1.40
Asbestos, sheet	0.29	Roofing composition	1.60
Asbestos board	0.48	Sawdust	1.03
Asbestos wood, pressed	0.84	Slate	10.50
Brass	754.00	Steel	313.00
Brick, dry conditions	4.00	Stone	10.00
Brick, wet conditions	5.00	Stucco	8.10
Carbon	4.40	Tin	420.00
Celotex	0.35	Water	2.24
Copper	1500.00	Woods:	
Concrete	6.30	Balsa wood	0.40
Corkboard	0.30	Cypress	0.70
Felt	0.26	Fir	1.01
Glass	3.20	Maple	1.21
Gypsum	2.90	Mahogany	0.91
Magnesia board	0.50	Oak	1.29
Magnesia, 85% magnesia, 15% asbestos	0.51	Pine	0.85
		Zinc	424.00

Now summing up all the foregoing facts relating to heat conduction, we arrive at the following statement: *The quantity of heat in Btu that will be conducted through a given piece of material in one hour will be directly proportional to the temperature difference between the two ends of the material, to the cross-sectional area of the material, to a constant depending on the nature of the material, and inversely proportional to the length of the heat path.* Expressing this in the form of an equation, we have the following:

$$H = \frac{AK(t_2 - t_1)}{l} \quad \ldots \ldots \ldots \quad (32)$$

in which

H = quantity of heat conducted through the material, Btu per hr.

A = cross-sectional area of material, sq ft.

K = coefficient of heat conductivity for material, Btu per hr per sq ft per in. thickness.[1]
t_2 = temperature of hot side of material, deg fahr.
t_1 = temperature of cold side of material, deg fahr.
l = thickness of material, in.

Example 1.

Suppose that a piece of sheet steel has an area of 30 sq ft, and is $\frac{3}{4}$ in. thick. If the temperature on one side of the sheet is 50 deg fahr, and that on the other side is 150 deg fahr, find the total quantity of heat that will be conducted through this sheet in 1 hr. The coefficient of heat conductivity for steel as given in Table VI is 240 Btu per hr per sq ft of area per in. of thickness per deg fahr difference in temperature.

Solution.

A = 30 sq ft.
K = 240.
t_2 = 150 deg fahr.
t_1 = 50 deg fahr.
$l = \frac{3}{4}$ in.

$$H = \frac{AK(t_2 - t_1)}{l}$$

$$H = \frac{30 \times 240(150 - 50)}{\frac{3}{4}} = 960{,}000 \text{ Btu per hr.}$$

Example 2.

Suppose a sheet of copper to have water at a temperature of 200 deg fahr in contact with one of its sides, and a temperature of 300 deg fahr on the other side. If the sheet has an area of 45 sq ft, and a thickness of $\frac{1}{4}$ in., how many Btu per hr are conducted through the copper sheet to the water? K for copper = 1500.

Solution.

$$H = \frac{AK(t_2 - t_1)}{l}$$

$$H = \frac{45 \times 1500(300 - 200)}{\frac{1}{4}} = 27{,}000{,}000 \text{ Btu per hr.}$$

[1] The coefficient of heat conductivity, K, is the quantity of heat in Btu which is transmitted per hour through a plate one inch thick, and one square foot in area, when the difference in temperature between the two sides is one degree Fahrenheit.

92. Determination of Coëfficient of Heat Conductivity by Experiment.—An apparatus commonly employed to determine the coefficient of heat conductivity for any material consists of a cubical box such as shown in Fig. 42. The top, bottom, and three sides of this box are constructed of material of relatively low heat conductivity, such as wood. The remaining side is constructed of the material to be tested. The air inside the box is heated by an electric heating unit to some temperature above that of the room, and this temperature is maintained constant by proper control of the heating unit. A small electric fan is placed inside the box to provide a circulation of air in order to assure a uniform inside temperature. The total quantity of heat supplied to the air inside the box is equal to the sum of the heat equivalent of the electrical energy consumed by the heating unit and the fan. (Referring to the electrical equivalent of heat in Chapter I, we find that 1055 watt-seconds = 1 Btu, a watt-second being defined as the application of one watt for one second.) Thus, if the apparatus is so arranged that we may measure the total wattage input to both the fan and heating unit, it is a simple matter to calculate the total heat energy supplied to the box, provided a record is kept as to the number of seconds that the test is run.

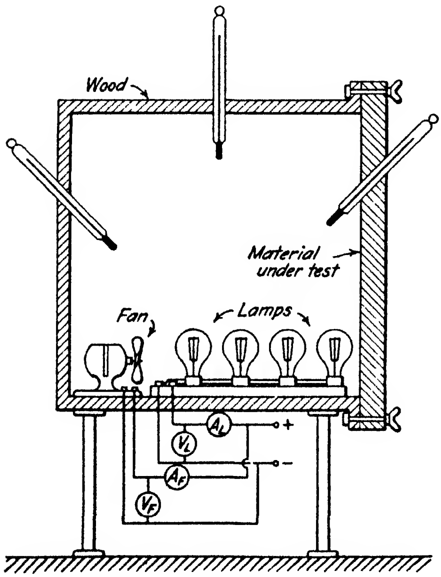


FIG. 42.—Thermal testing box.

By starting with a box having all six sides constructed of the same material, it is relatively simple to calculate the coefficient of heat conductivity for this material by the following equation:

$$K = \frac{Hl}{A(t_2 - t_1)} \qquad (33)$$

in which

K = coefficient of heat conductivity, Btu per hr per sq ft area per in. thickness, per deg fahr difference in temperature.
H = total quantity of heat supplied to box, Btu per hr.
l = thickness of box material, in.
A = total heat-transmitting area of box, sq ft.
t_2 = temperature of air inside box, deg fahr.
t_1 = temperature of air outside box, deg fahr.

After the value of K for the box material has been established, one side is removed, and the new material to be tested is substituted in its place. The box is again placed under test and the quantity of heat transmitted hourly determined. The difference between the calculated amount of heat that would have been conducted through the five sides of the original test box, and the actual heat input for the box with the new side, gives the amount of heat transmitted through the new side. This quantity of heat, H, which is conducted through the new side may be substituted in the foregoing equation to obtain the coefficient of heat conductivity for the material under test.

The method of determining the value of K as outlined in the foregoing paragraphs is particularly useful for establishing this coefficient for walls of unusual construction. A sample of the type of wall construction may be made to fit the sixth side of the test box, and its coefficient of heat conductivity determined for the wall as a whole.

93. Coefficient of Heat Transmission for Composite Walls.— A wall constructed of more than one material is known as a **composite wall.** For example, a wall such as shown in Fig. 43 is a composite wall. It is constructed of an 8-in. thickness of brick, a 2-in. air space, and finally, a 3-in. thickness of pine board.

In order to determine the quantity of heat that is transferred hourly through a wall of this type it is necessary to consider the convection and radiation of heat from the wall surfaces as well as the conduction through the walls themselves. Since it is difficult to measure separately the heat losses due to convection and radiation, they are usually combined as one loss.

The following formula gives the coefficient of heat transmission, U, for a composite wall such as shown in Fig. 43. U expresses the hourly quantity of heat that is transmitted through one square

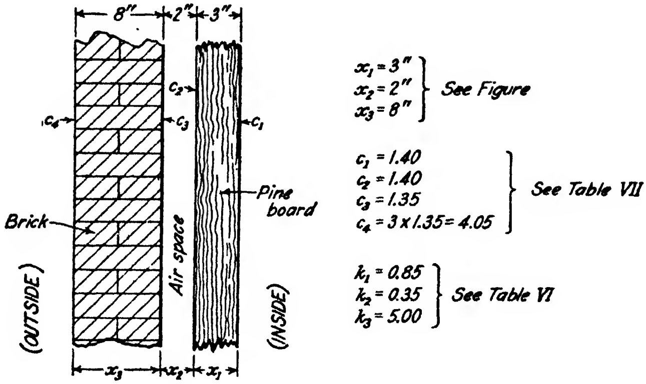


FIG. 43.—Composite wall having an air space between materials.

foot of wall (composed of alternate layers of materials separated by air spaces) for a temperature difference of one degree.

$$U = \frac{1}{\frac{1}{c_1} + \frac{x_1}{k_1} + \frac{1}{c_2} + \frac{x_2}{k_2} + \frac{1}{c_3} + \frac{x_3}{k_3} + \frac{1}{c_4}, \text{ etc.}} \quad . \quad (34)$$

In which

U = quantity of heat transferred through 1 sq ft of the wall per hr per 1 deg fahr difference in temperature, Btu per sq ft per hr per deg fahr.

x_1, x_2, x_3 = thickness in inches of each course of material.

k_1, k_2, k_3 = coefficient of conductivity of each material in Btu per hr per sq ft per in. thickness per deg fahr. (See Table VI.)

c_1, c_2, c_3, c_4 = combined coefficient of convection and radiation for each exposed surface in Btu transferred per sq ft per hr per deg fahr difference in temperature, between the surface and air in contact with surface. (For values of c consult Table VII.)

From Table VI the respective values of k for the wall shown in Fig. 43 are as follows: pine, $k = 0.85$; air, $k = 0.35$; brick, $k = 5.00$. The combined coefficients of convection and radiation from the various materials are obtained from Table VII and are as follows: pine, $c = 1.40$; brick, $c = 1.35$. Since c_4 is the

TABLE VII

COMBINED CONVECTION AND RADIATION SURFACE COEFFICIENTS FOR VARIOUS MATERIALS

Material	Coefficient c, for Still Air,* Btu per sq ft per hr per deg fahr
Asbestos	1.40
Brick	1.35
Concrete	1.30
Corkboard	1.25
Glass	1.50
Magnesia board	1.45
Plaster	1.00
Wood (finished)	1.40

* For moving air having a velocity of about 15 miles per hour, multiply the value of the surface coefficient given in Table VII by 3. That is, c for an outside wall equals 3 times the value of c given in above table.

coefficient for the outside of the brick wall its value will be $1.35 \times 3 = 4.05$ due to the effect of the moving air. (See footnote at bottom of Table VII.) The value of U for this composite wall may then be calculated as follows:

$$U = \frac{1}{\frac{1}{1.40} + \frac{3}{0.85} + \frac{1}{1.40} + \frac{2}{0.35} + \frac{1}{1.35} + \frac{8}{5.00} + \frac{1}{4.05}}$$

$= 0.0755$ Btu per sq ft per hr per deg fahr difference in temperature.

The value of U as calculated above is unusually small because the air in the air space between the walls was assumed to be at rest. In practice this is not true, for an actual motion of the air within this air space exists. This moving column of air conveys the heat away from the wall surfaces and no longer serves the part of a poor conductor of heat, but actually becomes quite an efficient medium for conveying heat. Since this is the case, the x/k factor for the air space is always omitted from the calculation of U. Hence in the foregoing example, the term 2/0.35, which represents

the x/k factor for the air space, would be dropped from the equation, and the value of U would be expressed as follows:

$$U = \cfrac{1}{\cfrac{1}{1.40} + \cfrac{3}{0.85} + \cfrac{1}{1.40} + \cfrac{1}{1.35} + \cfrac{8}{5.00} + \cfrac{1}{4.05}}$$

= 0.1326 Btu per sq ft per deg fahr difference in temperature.[1]

Example 1.

Determine the value of U for $\frac{1}{8}$-in. thick window glass.

Solution.

$c_1 = 1.50$ (Table VII).

$c_2 = 1.50 \times 3 = 4.50$ (Table VII).

$x_1 = 0.125.$

$k_1 = 3.20$ (Table VI).

$$U = \cfrac{1}{\cfrac{1}{1.50} + \cfrac{0.125}{3.20} + \cfrac{1}{4.50}} = 1.08 \text{ Btu per hr per deg fahr per sq ft.}$$

94. Flow of Heat through Composite Walls.—After calculating the coefficient of heat transmission, U, for a given wall, it is a simple matter to determine the total quantity of heat that will be transferred through this wall per hour under actual conditions. This is done by multiplying the value of U by the total area of the wall in square feet, and by the total temperature difference in degrees Fahrenheit that exists between the two sides of the wall. Expressing this as an equation we have:

$$H = UA(t_2 - t_1) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (35)$$

in which

H = total quantity of heat transferred per hour, Btu per hr.

U = coefficient of heat transmission of wall, Btu per sq ft per deg fahr.

A = total area of wall, sq ft.

[1] In the calculation of U for composite walls the x/k factor for the air space is always omitted.

t_1 = temperature of outside air, deg fahr.

t_2 = temperature of inside air, deg fahr.

Example 1.

Suppose that the wall shown in Fig. 43 has a total area of 80 sq ft, and that the temperature of the outside of the wall is 0 deg fahr, while the temperature on the inside is 70 deg fahr. Find the quantity of heat that will be transmitted through this wall in an hour's time. (Assume the air in the air space to be in motion.)

Solution.

U = 0.1326 Btu per sq ft per hr, per deg fahr. (See calculation, page 120.)

A = 80 sq ft.

t_1 = 0 deg fahr.

t_2 = 70 deg fahr.

$$H = UA(t_2 - t_1)$$
$$= 0.1326 \times 80(70 - 0)$$
$$= 742.6 \text{ Btu per hr.}$$

95. Heat Loss from a Room Due to Infiltration.—Since no building can be constructed so that it will be perfectly air-tight, a loss of heat is encountered owing to the infiltration of cold air through cracks, around windows and doors, and through other openings. Experiments have shown that the amount of heat lost from a room by infiltration of cold air may be expressed in terms of the linear feet of crack through which the leaks occur. It is customary practice to assume the following values for this loss:

$\frac{1}{32}$-in. crack = a heat loss of 1.2 Btu per lin ft of crack per hr per deg fahr difference in temperature.

$\frac{1}{16}$-in. crack = a heat loss of 2.4 Btu per lin ft of crack per hr per deg fahr difference in temperature.

The above values have been determined for a normal wind velocity of 15 miles per hour.

Example 1.

A certain room has 50 lin ft of $\frac{1}{32}$-in. crack around the perimeter of the windows. Determine the heat loss in Btu per hr due to infiltration of air, if the room temperature is 70 deg fahr and the outside temperature is 0 deg fahr.

Solution.

Total heat loss = $1.2 \times 50 \times (70 - 0) = 4200$ Btu per hr.

96. Heat Insulation.—There are two ways of considering the flow of heat through bodies by conduction. That is, one may think of the ease of flow, or the reverse effect, the resistance to flow. The choice of term depends upon the use to which the material is put. Copper tubing is introduced into a household hot-water heater so that the heat energy from the burning gas may be conducted through the walls of the tube to the water as quickly as possible. In English locomotives, the firebox is often made of copper because it is the best cheap metallic conductor of heat and accordingly permits a greater amount of steam to be made per square foot of surface exposed to the hot gases. We then say that copper is a *good conductor* of heat, that is, it permits the passage of large quantities of heat in a unit of time.

The outside of boilers is frequently covered with asbestos lagging in order to lessen the amount of heat conducted away from the boiler. We want a poor conductor of heat for this purpose, and we say that a *heat-insulating material* is employed. The property by virtue of which this insulator resists the flow of heat is its relatively low coefficient of heat conductivity.

Cork, sawdust, charcoal, gypsum, asbestos, various porous materials, and manufactured mixtures are commonly employed to lessen the amount of heat conducted away from warm bodies such as steam boilers, piping, and the like.

Refrigerating piping, cold-storage rooms, ice houses, etc., are protected with heat-insulating material in order to lessen the quantity of heat conducted in from outside. The common materials in use for this purpose are selected after consideration of their respective costs, heat conductivity, inflammability, strength to withstand handling, resistance to vibration, ability to stand large heat fluctuations, and their resistance to corrosion when subjected to heat and moisture.

A light, porous material that entangles a large amount of air within itself is often preferred as a heat-insulating material because the enclosed air is a very poor conductor. It should be observed, however, that these air spaces must not be so large as to allow convection currents to be set up in the material thereby destroying the insulating effect of the material. Asbestos forms an efficient heat-insulating material; besides being used alone, it is frequently employed to bind together other insulating compounds of magnesium, carbonates, and various silicates.

97. Insulation Devices.—The problem of keeping cold things cold, and hot things hot, has always been one of considerable importance. In cooking it is necessary that the food be maintained at a definite temperature for a given period of time until certain bacterial, mechanical, and chemical changes have taken place in the structure and composition of the food. It formerly was true that no one thought much about the heat that is lost from cook-stoves. So common has been the practice of using the stove for both heating and cooking that an " insulated stove " has only recently become a marketable article.

We now have fireless cookers in which food, previously heated to the cooking temperature, is placed. The cooker is provided with insulation to prevent the rapid loss of heat. Very hot soapstones are often placed inside of some of these cookers to provide a store of energy to offset the small loss of heat through the insulated walls.

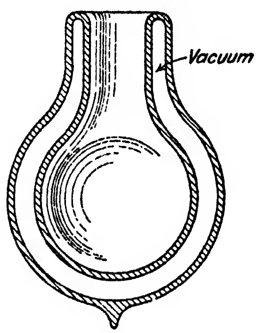


Fig. 44.—Dewar bulb.

Electric and gas stoves are now on the market in which the cooking is done in an insulated chamber which receives just enough heat from the resistance coils or from a gas flame to equalize the losses of heat through the insulation.

In order to store liquid air, Professor Dewar constructed a glass flask with a double wall. He exhausted the air from between the walls and silvered the inner surfaces of the vacuum chamber. The vacuum hinders greatly the conduction of heat through what would normally be an air space. The only sizable conduction loss is through the top of the flask. The silver produces a mirror surface on the two inner walls which reflect outward any incoming radiant heat rays without allowing the surfaces to absorb them. This reduces to a minimum the gain in heat energy from outside radiations. The gallon-size Dewar flask will keep liquid air for a period of two weeks or more. The construction of this type of heat-insulating flask is shown in Fig. 44.

Commercial forms of this flask, variously known as thermos bottles, vacuum bottles, etc., are in such common use as to be well known.

98. Convection.—As has been said, convection is the process of transferring heat from a hot body to a cold body by means of a conveying medium. The conveying medium is brought into contact with the hot body, gains heat from the hot body, and is moved on to the cold body to which it imparts this heat. A familiar example of this is found in the hot-air furnace system of heating a house. The air, being the conveying medium, is passed over the fire, thereby gaining heat. The heated air rising from the furnace through the pipes and registers imparts this heat to the different rooms in the house.

This circulation of heat may be due to natural causes or it may be produced by artificial means. These two modes of heat convection are known as (1) *natural convection,* (2) *artificial convection.*

99. Natural Convection.—In natural convection the process takes place automatically. Thus, when a portion of a fluid is brought in contact with a source of heat, this portion of the fluid becomes hot and expansion takes place. The expanded fluid then rises because of its reduced density. For example, when water is heated in an open vessel over a stove, the water at the bottom of the vessel is heated first and expands, becoming less dense than the rest of the water in the vessel, and consequently a motion is set up under the influence of gravity. The hotter portions of the fluid move away from the source of heat since they weigh less per unit of volume than the colder and more dense portions of the fluid. It follows naturally that the colder parts of the fluid become heated upon their arrival at the source of heat and finally move away to give room to the cooler and denser portions of the fluid. In this manner, natural convection currents are set up in a fluid which are continuously approaching and receding from the source of heat.

By studying the air currents in a steam-heated room, we find that cold air at the bottom of a radiator comes in contact with the hot surface of the metal and is heated by it. The heat gained by the air causes it to expand and its density to decrease below that of the cooler air in the room. The less dense warm air ascends to the upper portion of the room, just as a light liquid, such as kerosene oil, rises to the top of a heavier liquid, such as water. As the heated air rises, it comes in contact with the cooler walls and gives up a part of its heat to them. As soon as it is cooled by giving up

heat, this air becomes more dense than the air near the radiator. If the room is closed, this dense air will sink down in the parts of the room remote from the radiator, crowding upward the warm air near the radiator. After mixing with other air it will again pass by the radiator and repeat the trip about the room. Fig. 45 is intended to represent the circulation of air in a steam-heated room due to convection currents.

All ventilating and heating systems for houses, etc., take advantage of this principle to distribute the heated air about in each room. The hot-water system and the hot-air furnace depend upon natural convection to convey the heat from the furnace to

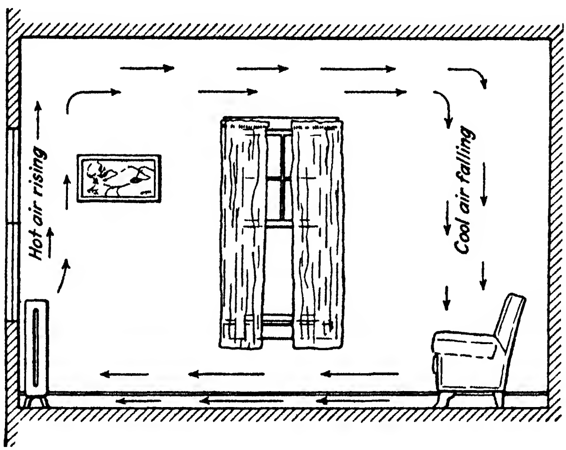


FIG. 45.—Convection currents in a steam-heated room.

the several rooms to be heated. Our winds, in most cases, are nothing more than convection currents on a large scale.

From the foregoing illustrations it is seen that heat energy is not transferred by convection except by the simultaneous movement of masses of the heat-carrying fluid. Convection currents may occur in liquids and gases, but a solid substance cannot have convection currents set up among its molecules and accordingly we cannot heat a solid internally by convection.

100. Artificial Convection.—When the conveying medium carrying the heat from the region of higher temperature to that of lower temperature is *forced or pumped* from the hot body to the cold body, the convection process thereby established is said to be

artificial. For example, the water flowing through the hot-water heating system in large buildings may be pumped (by means of a circulator) through the piping from the furnace to the different radiators and back again.

Suppose that the water leaves the furnace at a temperature of 180 deg fahr and that it is cooled to a temperature of 100 deg fahr by the time it arrives back from the radiators. It is evident that a drop in temperature of 180 − 100 = 80 deg fahr occurs while the water is circulating through the radiators and piping. Hence we may say that for every pound of water pumped through the heating system 80 Btu of heat are imparted to the surroundings.

Thus the quantity of heat that will be conveyed in a given length of time, say one hour, may be expressed by the following equation:

$$H = SW(t_h - t_c) \quad \text{. . . . . . .} \quad (36)$$

in which

H = quantity of heat conveyed, Btu per hr.
S = specific heat of conveying medium, Btu per lb per deg fahr.
W = weight of conveying medium passed per hour, lb per hr.
t_h = temperature of hot body from which conveying medium takes heat, deg fahr.
t_c = temperature of cold body to which conveying medium delivers heat, deg fahr.

Example 1.

Suppose a hot-water boiler circulates 568 lb of water per hour through the radiators and piping of a seven-room house. If the water leaves the boiler at a temperature of 190 deg fahr and returns at a temperature of 95 deg fahr, how many Btu are supplied hourly by this heating system?

Solution.

S = 1 Btu per lb per deg fahr.
W = 568 lb per hr.
t_h = 190 deg fahr.
t_c = 95 deg fahr.
$H = SW(t_h - t_c)$
$H = 1 \times 568(190 - 95)$ = 54,000 Btu per hr.

Example 2.

If a steam boiler passes 9000 lb of gaseous material at 520 deg fahr up the chimney in an hour, how many Btu per hr are lost in this manner?

Temperature of surrounding air = 80 deg fahr; specific heat of flue gas = 0.24 Btu per lb per deg fahr.

Solution.

$$H = SW(t_h - t_c)$$
$$H = 0.24 \times 9000(520 - 80) = 950{,}400 \text{ Btu per hr.}$$

It has been shown by experimentation that the change in temperature of a fluid in passing through a heated pipe is independent of the speed at which the fluid is caused to flow. Provided the operation is carried on within certain limits of length, cross-sectional area, and speed of flow this statement is true. This fact was first discovered by Reynolds, when he found that the outlet temperature of air forced through a hot tube was unaltered by a change in the speed of flow. Hence, it seems that the greater the rapidity of flow of the hot gases through a boiler, the greater would be the amount of heat transferred to the water contained in the boiler. For this reason many modern power plants equip their furnace with draft fans which increase the speed of the hot gases through the boiler.

101. Thermal Radiation.—From our common experience we are aware that hot bodies emit radiant energy, the amount of this emitted energy depending largely upon the temperature of the body. Hence, the quantity of radiant energy emitted by the filament of an incandescent lamp increases rapidly as the temperature of the filament is raised; and finally, at the higher temperatures, the filament appears "white hot." Radiation of this character, the intensity of which depends upon the temperature of the emitting body, is known as *thermal radiation.*

Unless the temperature of the emitting body is above 1000 deg fahr no *visual* radiation will be observed. However, we are well aware that the process of radiation takes place below this temperature, as is evidenced by the sensation of warmth experienced when a body slightly above body temperature is placed near the skin. Careful measurement shows that all bodies emit radiant energy at all temperatures except theoretically when the body is reduced to the temperature of absolute zero.

102. Radiant Emissive Power.—The rate at which a body emits thermal radiation depends upon (1) the temperature of the body and (2) the nature of its surface. *The total radiating power of a body is defined as the amount of radiant energy given off per*

unit of time per unit of surface area. This total radiating power may be expressed in Btu per sq ft per hr. For example, the total radiating power of the sun is approximately 127,000 Btu per sq ft per hr, which amounts to a little more than 50 hp per sq in.

Radiant energy falling upon a surface may be partly absorbed, partly reflected, and partly transmitted. Let us imagine radiant energy incident upon a black body. The radiant energy incident upon the black body will be entirely absorbed by it. However, if the radiant energy is incident upon a white body none of the energy is absorbed, but instead it is all reflected away from the white surface upon its arrival. Still again, if the body absorbing the radiant energy is dark gray in color, it is found that a large percentage of the incident energy is absorbed, while the remaining portion is reflected from the body without affecting its total energy content. In some cases, as in window glass, a large share of the incident radiation is transmitted though the material while but a very small amount is absorbed.

103. The Stefan-Boltzmann Radiation Law.—In 1879, Stefan advanced the theory that the total radiating power of a body is proportional to the fourth power of its absolute temperature. Stefan was led to this conclusion as the result of a careful investigation of the work of Tyndall. Tyndall's experiments had shown that the ratio between the radiation of a piece of platinum wire at 2192 deg fahr and the radiation of the same piece of wire at 977 deg fahr was as 11.7 is to 1. According to Stefan's law this ratio worked out mathematically as:

$$\frac{(2192 + 460)^4}{(977 + 460)^4} = \frac{11.6}{1}$$

This leads to the formal statement of Stefan's law, which is as follows:

$$H = k\left(\frac{T}{100}\right)^4 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (37)$$

in which

H = quantity of energy emitted by the radiating body, Btu per sq ft per hr.

k = radiation constant depending upon the character of the radiating surface (values for various materials given in Table VIII).

T = absolute temperature of the radiating surface, deg fahr.

Table VIII

RADIATION CONSTANTS OF VARIOUS MATERIALS *

Material	Temperature, deg fahr	k
Black body	70	0.1618
Brass, dull	100–660	0 0362
Cast iron, rough	105–480	0.1570
Copper, slightly polished	100–540	0.0278
Glass, smooth	70	0.1540
Gold plate, unpolished	70	0.1820
Ice	32	0.1060
Lampblack	32–100	0.1540
Sandstone, red	140–400	0.1000
Slate, smooth	140–400	0.1150
Wrought iron, clean, bright	85–225	0.0562
Wrought iron, dull, oxidized	70–670	0.1540
Wrought iron, highly polished	105–480	0.0467
Zinc, dull	120–545	0.0340

* Taken from Kent's "Mechanical Engineers' Handbook."

Example 1.

Determine the radiating power of a piece of slightly polished copper when at a temperature of 500 deg fahr.

Solution.

$$H = k\left(\frac{T}{100}\right)^4 = 0.0278\left(\frac{500 + 460}{100}\right)^4 = 236.1 \text{ Btu per sq ft per hr.}$$

Careful investigation of the radiation of energy from black bodies has proved the correctness of the Stefan-Boltzmann radiation law over the temperature range from 212 to 2300 deg fahr.

104. Wave Theory of Radiant Energy.—In the preceding discussion of radiant energy nothing has been said as to its nature. The most common theory of radiant energy pictures it as a kind of wave disturbance similar to the wave disturbance set up in water by dropping a stone into it. (See Fig. 46.) There are several significant differences, however, between heat waves and water waves. In the first place, radiant heat waves travel at the enormous speed of 186,000 miles per second, and are of a wavelength (distance from crest to crest) of 0.0127 in. for the longest

waves known. Second, the heat waves radiating from a hot body are invisible to the eye. However, when the temperature of the radiating body exceeds 1000 deg fahr the invisible heat radiations are accompanied by a visible radiation in the form of light. Third, radiant heat energy will pass through a vacuum without heating it, i.e., without loss of energy, and there are many substances such as hard quartz, glass, etc., that will permit radiant heat waves to pass through them with very small losses in energy.

If a piece of iron is heated to 400 deg fahr, the wavelength of the heat waves emitted from the iron is in the neighborhood of 53 millionths of an inch. At this temperature one cannot see any visual radiation (light), but can readily feel the effect of the thermal radiation. If the iron is further heated to, say, 1000 deg fahr,

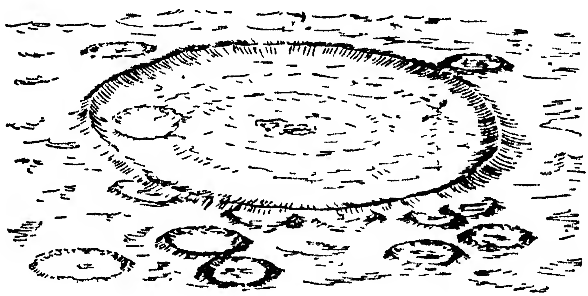


Fig. 46.—Wave motion set up by throwing a stone in water.

there will be a few waves whose wavelength is as short as 32 millionths of an inch. These radiations of shorter wavelength will affect the eye, and a faint red color will be observed. As the temperature is progressively raised other colors will be seen in the following order:

Dull red,	1300 deg fahr	=	0.000,030-in. wavelength.
Cherry red,	1700 deg fahr	=	0.000,026-in. wavelength.
Orange,	2100 deg fahr	=	0.000,022-in. wavelength.
White,	2350 deg fahr	=	0.000,019-in. wavelength.
Dazzling,	2700 deg fahr	=	0.000,017-in. wavelength.

Extensive experimentation on the part of W. Wien resulted in the formulation of a law which relates the temperature of a radiating body with the wavelength of the energy that it radiates.

Wien's law states that, as the temperature of the emitting body increases, the wavelength of each constituent of the radiation is shortened in proportion to the rise in temperature.

He also showed by experimentation that for radiation at a given temperature there is one particular wavelength that is favored more than the rest, since more energy is emitted of that particular wavelength than with any of the others. Wien found that the wavelength corresponding to the maximum energy varied inversely as the absolute temperature of the radiating body, which, expressed in equational form, gives:

$$\lambda_m T = \text{a constant} = 0.2045 \quad . \quad . \quad . \quad . \quad (38)$$

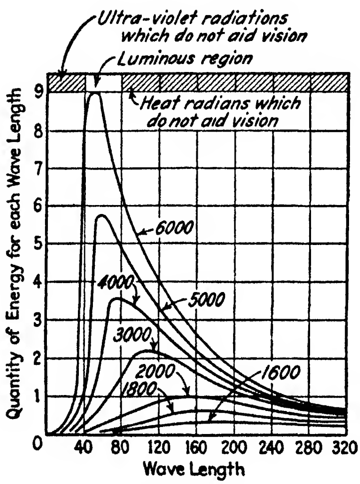


FIG. 47.—Distribution of energy in the spectrum.

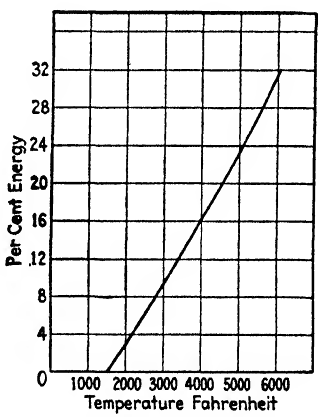


FIG. 48.—Relation between percent of energy in visible spectrum and temperature.

in which

λ_m = wavelength at which maximum emission occurs, in.

T = absolute temperature of the emitting body, deg fahr.

The constant 0.2045 in.-deg is the result of continued investigations over a range of temperatures from 1120 to 3030 deg fahr.

Wien's formula may be tested by plotting curves showing the distribution of energy in the spectrum for constant temperatures as illustrated by Fig. 47. The area inclosed under these curves and the horizontal axis of the graph represents the amount of

energy emitted per unit of area by the radiating body in a unit of time. It will also be noticed that as the temperature of the radiating body is increased, the wavelength of maximum intensity shifts gradually toward the shorter wavelengths. This shifting of the curve with increases in temperature results in a larger area, and consequently a larger amount of energy, to fall in the visible spectrum. Fig. 48 is intended to show the percentage of energy included in the visible spectrum corresponding to various Fahrenheit temperatures. Applying the information offered by the curves in Figs. 47 and 48 to the practical problem of incandescent illumination it follows that the higher the temperature at which the lamp is operated the greater will be its efficiency.

Carbon lamp filaments may be operated at very high temperatures, but above 3450 deg fahr the rate at which the carbon sublimes is so great that it is not practicable to use temperatures higher than this. The sublimate is deposited on the glass bulb, and soon blackens the interior of the lamp. Tantalum and tungsten do not readily sublime below their melting point, so that they may be operated at higher temperatures than carbon filaments, and therefore make more efficient lamps. Standard Mazda lamps are usually operated at a temperature of 4200 deg fahr; the newer Mazda lamps which are filled with nitrogen operate successfully at about 5000 deg fahr.

105. The Quantum Theory of Radiant Energy.—In the latter part of the nineteenth century the German physicist Max Planck proposed what is known as the Quantum Theory. This theory assumes that energy radiated from bodies in the form of heat, light, etc., is not a continuous flow but is made up of particles given off at intervals extremely close together and is like the stream of bullets shot from a machine gun rather than the flow of a stream of water.

Planck set forth that there was a unit of energy which could not be subdivided, and that the bursts of energy radiated from an active body were composed of multiples of this unit. This unit he called the **quantum.** The number of quanta included in one emitted charge and the rate of emission determine the intensity of the energy and the form which it assumes to the observer.

Thus, according to Planck's theory of radiation, we are to consider the emission of energy from a body to take place in the form of little bundles rather than in the form of a continuum.

106. Relation between Wave and Quantum Theories.—The foregoing article indicates that the rate of emission of quanta determines the form which the emitted energy assumes. In the wave theory it has been pointed out that the wavelength (or, inversely, the frequency) determines the form of the energy—whether light, heat, electromagnetic disturbances, etc. The tie-up between the two theories lies in the fact that the frequency conception of the wave theory and the rate of emission conception of the quantum theory are essentially the same thing. Hence the two theories differ only in their assumption as to what the energy itself is composed of rather than in an interpretation of its effects.

SUMMARY OF CHAPTER VI

The transmission of heat may take place by three different processes: that is, by CONDUCTION, by CONVECTION, or by RADIATION.

Heat can only be transmitted from body A to body B when body A is at a higher temperature than body B.

CONDUCTION is the process of transmitting heat through a substance without any apparent motion of the substance as a whole. The equation expressing the rate of conduction of heat through a body is stated as follows:

$$H = \frac{AK(t_2 - t_1)}{l}$$

The COEFFICIENT OF HEAT CONDUCTIVITY, K, represents the quantity of heat in Btu which is transmitted per hour through a plate one inch thick and one square foot in area, when the temperature difference between the two sides of the plate is one degree Fahrenheit.

In order to determine the quantity of heat transmitted hourly through a composite wall, it is first necessary to determine the TRANSMISSION COEFFICIENT, U, for the entire wall by means of the following equation:

$$U = \frac{1}{\frac{1}{c_1} + \frac{x_1}{k_1} + \frac{1}{c_2} + \frac{x_2}{k_2} + \frac{1}{c_3} + \frac{x_3}{k_3} + \frac{1}{c_4}}$$

The total quantity of heat transmitted hourly through the entire wall is given by the equation:

$$H = UA(t_2 - t_1)$$

CONVECTION is the process of transmission of heat in a fluid mass by means of the motion of the particles of that mass. The motion of the particles of the mass may be due to natural causes (difference in density) or may be the result of artificial circulation.

RADIATION is the process of transmitting heat through space by means of a wave motion. The heat from a bonfire comes to us as radiant heat.

The STEFAN-BOLTZMANN radiation law states that the quantity of radiant energy emitted by a unit surface of a radiating body in a unit of time is in direct proportion to the fourth power of the absolute temperature of the body. Expressing this as an equation, we have,

$$H = k\left(\frac{T}{100}\right)^4$$

REVIEW PROBLEMS ON CHAPTER VI

1. If steam at 153 deg cent gives up 68.0 kw per sq ft per hr through cast iron to air at 20 deg cent, what is the value of K for this cast iron? Thickness = $\frac{1}{4}$ in.

2. The coefficient of heat conductivity for pasteboard is given as 0.397 calorie per hr per deg cent per cm thickness per sq cm cross-sectional area. What is the value of K for this pasteboard in the customary English units?

3. Compute the quantity of heat lost per hour through a plate glass window $\frac{3}{8}$ in. thick and 8 ft by 12 ft in area. Temperature inside is 70 deg fahr; temperature outside is 0 deg fahr.

4. Kent's "Handbook" gives the coefficient of heat conductivity for asphalt-cork composition as 0.484 Btu per hr per sq ft cross-sectional area per in. of thickness per deg fahr. What is the corresponding value for the metric system expressed in calories per hr per sq cm cross-sectional area per cm thickness per deg cent?

5. Kent's "Handbook" shows six values of the coefficient of heat conductivity for asbestos in the regular English units. The value at 32 deg fahr = 0.048; at 212 deg fahr = 0.346; at 392 deg fahr = 0.451; at 572 deg fahr = 0.499; at 752 deg fahr = 0.548; and at 1112 deg fahr = 0.644.

Plot a curve showing the effect of temperature on the conductance of asbestos. State what this curve shows.

6. The total hourly heat loss from a building is found to be 63,000 Btu. If the building is heated by means of a hot-water system, how many pounds of water per hour must be circulated if the water leaves the boiler at 203 deg fahr and returns at 103 deg fahr?

7. If the boiler in problem 6 has an efficiency of 70 percent, how many pounds of coal must it burn in an hour's time to supply the necessary heat to the water? Heating value of the coal burned is 14,200 Btu per lb.

8. Discuss the wave theory as to the nature of radiant heat energy. What is the Stefan-Boltzmann radiation law?

CHAPTER VII

FUELS AND THEIR COMBUSTION

107. Definition of a Fuel.—*Any substance that can be burned in such a way as to produce heat in commercial quantities is called a fuel.* For a fuel to be of practical value, however, it is essential that it be obtainable in quantity and at a reasonable price.

108. Classification of Fuels.—Fuels for power purposes are classified according to their physical characteristics, that is, as solids, liquids, and gases. Table IX lists several of the more common of these fuels.

TABLE IX

CLASSIFICATION OF FUELS

Solid Fuels	Liquid Fuels	Gaseous Fuels
Anthracite coals Bituminous coals Lignite Peat Wood Charcoal Sawdust	Crude petroleum and its distillates Coal-tar oil Water-gas oil	Natural gas Illuminating gas Producer gas Coke-oven gas Blast-furnace gas

Since coal is commercially the most commonly used fuel, we shall start our discussion by considering first its formation and then its composition and characteristics.

109. Formation of Coal.—Coal is a substance resulting from the action of great pressures and temperatures on the remains of prehistoric vegetation. It consists essentially of a collection or deposit of vegetable material that has been undergoing slow changes for thousands of years until it has finally arrived at its present state. Coals differ in character according to the variation

of such factors as time of formation, depth of bed, disturbance of bed, introduction of foreign material, etc.

110. Composition of Coal.—The principal constituent of all coal is carbon. Other constituents are hydrogen, oxygen, nitrogen, sulphur, moisture, and impurities. The effect of the moisture, nitrogen, and impurities is to lower the heating value of the fuel. The remaining elements are known as the **combustible** in the coal.

111. Analysis of Coal.—A coal analysis is a laboratory determination of the percentage composition of the various constituents present in a given sample of coal. In common practice an analysis is reported in two different forms, i.e.:

1. A *proximate analysis* which determines the percentages of moisture, fixed carbon, volatile matter, and ash.
2. An *ultimate analysis* which reduces the coal to its elementary constituents of carbon, hydrogen, oxygen, sulphur, and nitrogen.

112. Coal Sampling.—Before either a proximate or an ultimate analysis may be conducted, it is necessary to select a fair sample of coal from the coal supply. This may be done by a process known as *quartering*. At least 200 lb of coal is selected by the shovelful from various parts of the coal pile. This quantity of coal is spread out in a flat circular pile on a floor and crushed with a suitable crushing tool until the lumps of coal are no larger than $\frac{1}{2}$ in. in diameter. After the crushing operation is completed, the pile is quartered and opposite quarters are discarded. The remaining two quarters are spread out into a new circular pile and the crushing operation is continued until the size of the lumps has been reduced to $\frac{1}{4}$ in. in diameter. In turn, this pile is quartered in the same manner as before and opposite quarters again rejected. This process of crushing, quartering, and rejecting is continued until 5 to 10 lb of coal remain. This final sample is carefully collected and placed in an air-tight glass container to be sent directly to the laboratory for analysis.

113. Proximate Analysis of Coal.—As has been said, a proximate analysis of coal is a determination for five quantities: namely, moisture, volatile matter, ash, fixed carbon, and sulphur. It is customary practice to express the relative percentages of the constituents on a weight basis in such a manner that the sum of the first four shall equal 100 percent, the percentage of sulphur by

weight being determined separately. Table X on page 139 gives the proximate analysis for several American coals.

Moisture.—Moisture in coal lowers the heat-producing value of the coal. It is the source of a direct loss, since heat is required for its evaporation. The percentage by weight of moisture is usually determined by drying part of the sample in a shallow open dish at 90 deg fahr for a period of 12 hr. *The loss in weight of the sample due to the drying is the moisture in the coal.* The ratio between the loss in weight and the original weight is the percentage by weight of moisture in the original sample.

Volatile Matter.—The volatile matter is that part of the coal that may be driven off in gaseous form at a comparatively low temperature. These combustible gases, which are essentially hydrocarbons, form the flaming constituents of the coal.

The percentage by weight of volatile matter is commonly determined by heating about one gram of the moisture-free sample to about 1740 deg fahr in a tightly closed platinum crucible for a period of 7 min. The loss in weight of the sample during this heating process is caused by the passing off of the volatile matter.

Ash.—Ash is that residue that is left after the complete combustion of the coal. It may be determined by heating the sample left after the moisture and volatile matter have been driven off to such a temperature that the sample is completely burned. This is usually done by placing the moisture-free and volatile free sample in an open crucible to which oxygen is supplied and heating it by means of a blast lamp. This process drives off all the constituents of the coal except the ash; thus the weight of the residue is the ash content of the sample.

Fixed Carbon.—The term fixed carbon refers to that carbon that is not combined with any other substance. The fixed carbon does not comprise the total carbon content of the coal, since, as we know, a portion of the carbon combines with hydrogen to form hydrocarbons or volatile matter. The percentage of fixed carbon is found by subtracting the sum of the weights of the moisture, volatile matter, and ash from the weight of the original sample.

Sulphur.—The determination of the percentage of sulphur present in coal is usually made as a separate analysis by leaching the ash with water and adding a chemical known as barium chloride, which separates the sulphur in such a form that its amount may be found by weighing.

114. Ultimate Analysis.—The purpose of an ultimate analysis is to reduce the coal to its elementary constituents of carbon, hydrogen, oxygen, nitrogen, and sulphur. An analysis of this nature is one which requires the services of an expert chemist, for a high degree of skill is essential to secure reliable results. It is customary to report an ultimate analysis of coal in such a manner that the sum of the percentages of the various constituents shall equal 100 percent.

115. Methods of Reporting Proximate and Ultimate Analyses.—Both the proximate and ultimate analyses of coal may be reported on three different bases, i.e.:

1. Coal " as received."
2. Coal " dry."
3. Coal moisture- and ash-free, or " combustible."

The analysis of coal on an " as received " basis includes the percentage by weight of each of the constituents of the fuel. The " dry " coal analysis excludes the percentage of moisture in the report; the analysis on the " combustible " basis excludes both the moisture and the ash in the recorded results. Table X gives the proximate analysis on an " as received " basis and the ultimate analysis of several typical coals, the heating value per pound being indicated in the last column of the table. It should be noted that the heating value per pound of coal " as received " is lower than the heating value per pound of " dry coal " or per pound of " combustible."

116. Combustion.—*Combustion may be defined as any process of burning which evolves heat.* Oxygen is the commercial supporter of combustion; thus, a **combustible** may be defined as a substance capable of combining with oxygen to produce heat. In the power field the term combustible is applied commonly to those substances that may combine with oxygen to produce heat in sufficient quantity to be classified as a fuel.

In order for any substance to burn it must be heated to a sufficient temperature to kindle. Thus we see that the mere introduction of a combustible into the presence of oxygen does not of necessity result in combustion, combustion taking place only when the combustible is heated to or above its **ignition temperature.**

Table X
ANALYSES OF TYPICAL AMERICAN COALS

Kind of Coal	Proximate				Ultimate					Heating Value, Btu		
	Moisture	Volatile Matter	Fixed Carbon	Ash	Sulphur	Hydro-gen	Carbon	Nitrogen	Oxygen	Air Drying Loss	As Received	Moisture and Ash Free
Rhode Island Graphitic Coal	13.9	2.5	63.2	20.4	1.34	1.84	62.09	0.19	14.14	11.4	9,040	13,770
Pennsylvania Anthracite	3.43	6.79	78.25	11.53	0.46	2.52	78.85	0.77	5.87	2.5	12,782	15,030
Pocahontas Coal	2.8	14.5	77.4	5.33	0.64	4.56	83.39	1.03	5.05	2.2	14,550	15,800
New River Coal	2.94	20.11	73.1	3.85	1.12	5.04	82.60	1.46	5.93	2.1	14,582	15,625
Pittsburgh Bed	3.39	31.79	56.46	8.36	1 05	5.07	74.42	1.39	9.71	2.4	13,699	15,522
Alabama Coal	4.83	31.40	52.40	11.37	0.74	5.26	71.61	1.23	9.79	3.9	12,780	15,250
Illinois Coal	12.39	36.89	41.80	8.92	3.92	5.85	61.29	1.00	19.02	8.4	11,399	14,500
Iowa Coal	13.88	36.94	35.17	14.01	6.15	5.52	54.68	0.84	18.8	9.8	10,244	14,200
Kansas Coal	4.99	32.68	49.36	12.97	4.28	4.98	67.34	1.08	9.35	1.3	12,242	14,900
Arkansas Coal	2.91	12.65	66.93	17.51	3.12	3.60	70.88	1.17	3.72	1.7	12,312	15,440
Oklahoma Coal	4.61	37.00	47.25	11.14	3.63	4.92	67.36	1.48	11.46	1.2	12,319	14,600
Colorado Anthracite	3.0	3.0	86.5	7.5	0.69	2.67	83.20	1.48	4.48	1.1	13,500	15,100
Colorado Bituminous	4.06	34.48	52.84	8.62	0.65	5.34	71.18	1.24	12.97	2.4	12,888	14,750
Colorado Lignite	23.07	31.20	35.60	10.13	0.21	5.77	47.69	0.64	35.56	14.5	8,030	12,000
Wyoming Sub-Bituminous	22.38	31.85	39.42	6.35	1.16	6.32	52.25	1.19	32.73	8.1	9,247	12,900
Texas Lignite	34.7	32.23	21.87	11.20	0.79	6.93	39.25	0.72	41.11	24.6	7,056	13,000
North Dakota Lignite	38.92	25.54	30.15	5.39	0.48	6.89	39.34	0.68	47.22	31.7	6,739	12,100
Florida Peat	17.2	51.01	24.85	6.93	0.49	6.14	47.85	2.89	36.19	50.0	6,403	8,420
Alaska Bituminous	7.77	7.40	75.59	9.24	0.66	4.07	73.99	1.41	10.63	6.0	12,569	15,140
Alaska Lignite	34.42	23.92	27.80	13.86	1.38	6.41	35.46	0.63	42.26	30.3	6,300	12,180

Courtesy Combustion Engineering Corporation.

117. Chemistry of Combustion.—In the process of the burning of a fuel the heat-producing elements (carbon, hydrogen, and sulphur) are driven off in gaseous form and unite with the oxygen of the air to produce heat. In order to understand fully the chemical reactions taking place during the combustion of a fuel, it is essential to have a knowledge of the structure of matter.

It is common belief that all substances are made up of atoms, which are very small particles of the chemical elements of which the substance is composed. These elemental atoms combine in groups to form molecules, the molecule being the smallest possible particle to have the character of the original substance. Thus we say that a molecule of water is the smallest particle of water which exists. However, the molecule of water may be subdivided into atoms of the elements hydrogen and oxygen. For convenience, elements are designated by symbols; for example, the symbols C, H, N, O, S represent one atom of the elements carbon, hydrogen, nitrogen, oxygen, and sulphur, respectively.

The physical structure of matter is such that all the chemical elements follow exact laws when they combine with one another. Thus one pound of an element such as carbon will always combine with a definite weight of oxygen when forming carbon dioxide. Also a very definite quantity of heat will be evolved when a combination of this nature takes place; in the combination of carbon with oxygen to form carbon dioxide, 14,600 Btu are always liberated per pound of carbon burned.

Hence, *when a given weight of a combustible element burns it combines with a definite weight of oxygen in doing so; and the process always evolves a fixed quantity of heat.* Table XI gives the com-

TABLE XI

COMBINING WEIGHTS OF ELEMENTS

Name of Element	Symbol	Combining Weight
Carbon.	C	12
Hydrogen.	H	1
Sulphur.	S	32
Oxygen.	O	16
Nitrogen.	N	12

bining weights of some of the more common elements encountered in solid fuels.

118. Combustion of Carbon.—Carbon, as we already know, is the principal heat-producing element of most fuels. If the combustion of the carbon is complete, each atom of carbon will unite with two atoms of oxygen to form one molecule of carbon dioxide, thus:

$$C + O_2 = CO_2 \quad \ldots \ldots \quad (39)$$

The combining weights involved are, from Table XI, C, 12; O_2, 32; Hence:

$$12 + 32 = 44$$

Dividing by 12,

$$1 + 2\tfrac{2}{3} = 3\tfrac{2}{3}$$

Thus we see that *one pound of carbon will combine with $2\frac{2}{3}$ lb of oxygen to form $3\frac{2}{3}$ lb of carbon dioxide* when the combustion is perfect. *The quantity of heat liberated by the perfect combustion of this one pound of carbon will be 14,600 Btu.*

However, if there is a scarcity of oxygen at the time of combustion, the combustion is not complete; that is, each atom of carbon unites with only one atom of oxygen instead of with two as before. In this case, carbon monoxide gas (CO) will be formed instead of carbon dioxide (CO_2). This chemical combination may be expressed as follows:

$$2C + O_2 = 2CO \quad \ldots \ldots \quad (40)$$

Introducing the combining weights of carbon and oxygen we have:

$$(2 \times 12) + 32 = 56$$

Dividing by 24,

$$1 + 1\tfrac{1}{3} = 2\tfrac{1}{3}$$

Hence we see that *one pound of carbon will combine with $1\frac{1}{3}$ lb of oxygen to form $2\frac{1}{3}$ lb of carbon monoxide when the combustion is incomplete. In this case only 4440 Btu are liberated per pound of carbon burned.* If the carbon in a coal is not burned under conditions of perfect combustion, a very distinct loss of available heat is encountered; therefore, it is essential that sufficient air be supplied during the process of combustion of coal if the maximum heating value of the coal is to be obtained.

119. Combustion of Sulphur.—Sulphur in a fuel combines with the oxygen of the air to form sulphur dioxide as the gaseous product of combustion. The chemical reaction that takes place may be written as follows:

$$S + O_2 = SO_2 \qquad \ldots\ldots \qquad (41)$$

The combining weights entering into this reaction are:

$$32 + 32 = 64$$

Dividing by 32,

$$1 + 1 = 2$$

That is, *one pound of sulphur will unite with one pound of oxygen to form 2 lb of sulphur dioxide gas. The quantity of heat that is liberated by the burning of one pound of sulphur to sulphur dioxide is 4000 Btu.*

120. Combustion of Hydrogen.—Hydrogen when burned combines with oxygen to form water vapor. This chemical reaction is expressed by the following equation:

$$2H_2 + O_2 = 2H_2O \qquad \ldots\ldots \qquad (42)$$

A consideration of the combining weights gives the following:

$$(2 \times 2) + 32 = 36$$

Dividing by 4,

$$1 + 8 = 9$$

Thus, *one pound of hydrogen will combine with 8 lb of oxygen to form 9 lb of water vapor. The quantity of heat that would be liberated by the complete combustion of one pound of hydrogen to water vapor is 62,000 Btu.*

Since the ratio of hydrogen to oxygen in water vapor is 1 to 8 it will require 8 lb of oxygen for the complete combustion of one pound of hydrogen; but it must be remembered that a part of the hydrogen present in a fuel is already in the form of water or moisture, and therefore will not be of any value as a heat-producing constituent. Numerically the percentage of unavailable hydrogen will be equal to the percentage of oxygen present in the fuel divided by 8, which is the combining ratio of oxygen with hydrogen to form water. Thus the percentage of available hydrogen present

from a heat-producing standpoint will be equal to H, the total percentage of hydrogen present in the fuel, minus O/8, the percentage of hydrogen already in combination with oxygen as water. This percentage of available hydrogen then equals (H − O/8); and *the quantity of heat produced by the combustion of the available hydrogen equals 62,000* (H − O/8).

121. Calculation of the Heating Value of a Coal from the Ultimate Analysis.—From a study of the foregoing theory of combustion it is seen that it is possible to predict the heating value of a fuel if the ultimate analysis of the fuel is known. Dulong has stated the quantity of heat given off per pound of dry fuel as follows:

$$\text{Btu per lb of dry fuel} = 14{,}600C + 62{,}000(H - O/8) + 4000S \qquad (43)$$

where C, H, O, and S represent the proportionate parts by weight of carbon, hydrogen, oxygen, and sulphur present in a one-pound sample of the fuel. The coefficients in this equation represent the quantity of heat given off by the complete combustion of one pound of carbon, hydrogen, oxygen, and sulphur respectively. The expression (H − O/8) represents the total percentage of hydrogen available for producing heat. (Consult Article 120.)

Example 1.

An ultimate analysis of a coal on a percentage-by-weight basis gave the following data: carbon = 81.52, hydrogen = 5.02, oxygen = 3.69, nitrogen = 1.70, sulphur = 0.91, ash = 7.16. Calculate the heating value of the coal by means of Dulong's equation.

Solution.

$$\text{Btu per lb of dry coal} = 14{,}600C + 62{,}000(H - O/8) + 4000S$$

$$\text{Btu per lb of dry coal} = 14{,}600 \times 0.8152 + 62{,}000(0.0502 - 0.0369/8) + 4000 \times 0.0091$$

$$\text{Btu per lb of dry coal} = 14{,}765 \text{ Btu.}$$

122. Calorimetric Determination of the Heating Value of Coal.—Although the foregoing analyses are useful in the determination of the general characteristics of a fuel and may be used in an approximate determination of the heating value of the fuel,

wherever an accurate determination of the heating value is required it is good practice to resort to the use of a " bomb calorimeter " such as illustrated in Fig. 8 in Chapter II. As stated in Article 32, this instrument completely burns the fuel to be tested under oxygen pressure and the heat evolved by the combustion is absorbed by the surrounding water, the amount of the heat delivered being equal to the (weight of the water + water equivalent of the calorimeter) × rise in temperature of the water.

123. High and Low Heating Value.—The heating value of a fuel as obtained by the process of calorimetry is known as the *higher heating value*, since it is higher than that which is realized under actual operating conditions, by an amount equal to the latent heat of evaporation of the water contained in the fuel. The *lower heating value* of a fuel is equal to the higher heating value minus the quantity of heat lost by the evaporation of water.

It is common practice to use the higher heating value for all calculations pertaining to boiler test work.

124. Determination of Heating Value of a Fuel from Proximate Analysis.—Fig. 49 is presented for determining the probable heating value of a fuel from data obtained from a proximate analysis of the fuel. The curve is based on data taken from 65 samples of coal, and is corrected within 2 percent average. The Btu per pound of combustible is plotted on the vertical axis; the corresponding percentage of fixed carbon contained in one pound of combustible is plotted on the horizontal axis.

Example 1.

Determine the heating value in Btu per lb on an " as received " basis for a coal showing the following proximate analysis: volatile combustible, 30.7 percent; fixed carbon, 55.0 percent; moisture, 5.8 percent; and ash, 8.5 percent.

Solution.

Volatile combustible = 30.7
Fixed carbon = 55.0

Total combustible = 85.7 percent

Fixed carbon per pound of combustible = 55 ÷ 0.857
= 64.0 percent

Btu per lb of combustible (from curve of Fig. 49) = 15,280 Btu.

Btu per lb of coal " as received " = 15,280 × 0.857
= 13,095 Btu.

125. Quantity of Air Required for Combustion of Coal.—The supply of oxygen that is used to support the combustion of coal is usually taken from the air. Since 23 percent of dry air by weight is oxygen, it is necessary to supply 1/0.23 = 4.35 lb of dry air for each pound of oxygen delivered to the fuel bed. The remaining 3.35 lb consists of nitrogen and other inert gases which pass through the fuel bed and are heated without helping in the process of combustion. Hence the inert gases in air serve no

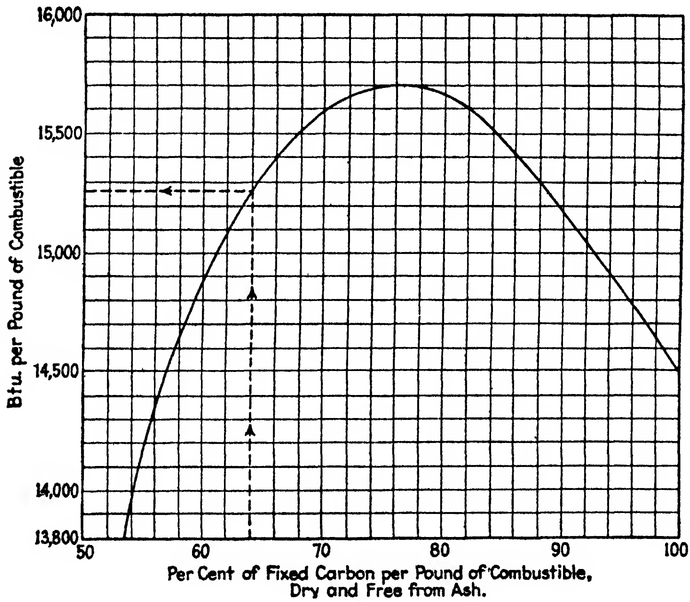


FIG. 49.—Curve for determining the heating value of a coal from its proximate analysis.

useful function in combustion; they are on the contrary a source of direct loss.

From Article 118 we found that it requires $2\frac{2}{3}$ lb of oxygen to burn one pound of carbon to carbon dioxide. Now if one pound of oxygen is contained in 4.35 lb of air, it will be necessary to supply $2\frac{2}{3} \times 4.35 = 11.6$ lb of air for the complete combustion of one pound of carbon to carbon dioxide.

Let us next consider sulphur. It takes one pound of oxygen to burn one pound of sulphur to sulphur dioxide. Thus, it will

require $1 \times 4.35 = 4.35$ lb of air for the complete combustion of one pound of sulphur.

We know that 8 lb of oxygen are required for the combustion of each pound of hydrogen to water vapor. Thus, it will take $8 \times 4.35 = 34.8$ lb of air for the complete combustion of one pound of hydrogen.

The sum of these three items gives the following equation for the weight of air necessary for the complete combustion of one pound of coal:

Weight of air required per pound of coal, lb

$$= 11.6C + 34.8(H - O/8) + 4.35S \qquad (44)$$

in which

$$\left.\begin{array}{l} C = \text{percentage of carbon} \\ H = \text{percentage of hydrogen} \\ O = \text{percentage of oxygen} \\ S = \text{percentage of sulphur} \end{array}\right\} \begin{array}{l}\text{present in 1 lb coal} \\ \text{by ultimate analysis}\end{array}$$

Example 1.

A Pocahontas coal yields the following ultimate analysis on an "as fired" basis: sulphur, 0.64 percent; hydrogen, 4.56 percent; carbon, 83.39 percent; nitrogen, 1.03 percent; oxygen, 5.05 percent. Determine the theoretical quantity of air in pounds that is required to support conditions of perfect combustion for each pound of coal fired.

Solution.

$$\text{Weight of air per lb of coal} = 11.6C + 34.8(H - O/8) + 4.35\,S$$
$$= (11.6 \times 0.8339) + 34.8(0.0456 - 0.0505/8)$$
$$+ (4.35 \times 0.0064) = 11.07\,\text{lb}.$$

126. Actual Quantity of Air Required for Combustion of Coal.—The total weight of air required per pound of coal burned in the actual furnace will be found to be greatly in excess of that which is theoretically required. If the coal is fired in the proper manner, the air properly mixed with the gaseous products of combustion, and the furnace temperature kept sufficiently high, 50 to 100 percent of excess air will suffice. However, if furnace conditions are poor, as high as 200 percent excess air may be necessary in order that combustion be complete.

127. Combustion of Coal.—The process of combustion of coal in a furnace may be better understood by a study of Fig. 50.

Assume that here we have an incandescent fuel bed, and that we shovel on a supply of fresh coal. First, two things happen: the moisture contained in the fresh coal is driven off as steam; and the volatile matter of the coal is driven off as combustible gases. If sufficient air is admitted through the firing door to unite with these volatile hydrocarbon gases, they will be completely burned and thus give up heat to the boiler above. This is the reason for admitting air through the firing door over the top of the fuel bed.

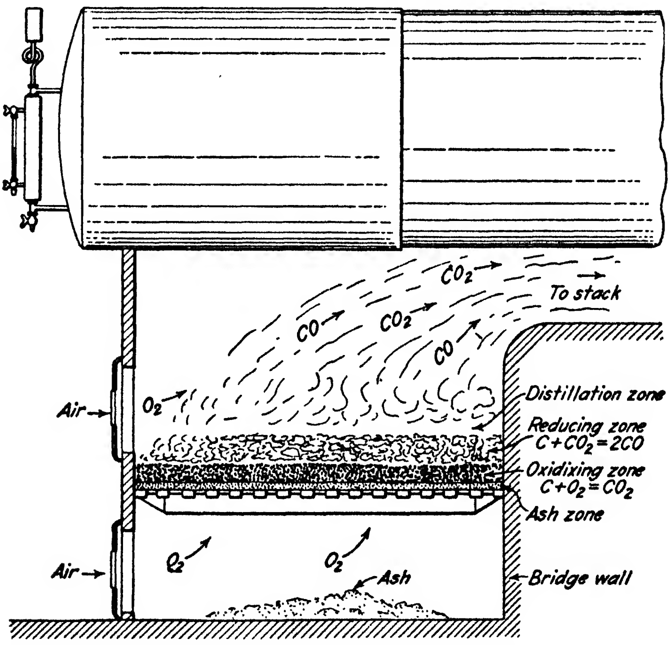


FIG. 50.—Diagram showing chemical reactions taking place during the combustion of coal.

After the moisture and volatile gases have been driven from the fresh coal, only fixed carbon and ash remain. This carbon in the lower part of the fuel bed combines with the air supplied under the grate and is burned to carbon dioxide ($C + O_2 = CO_2$). This process of oxidation of carbon gives the name "oxidizing zone" to the fuel-bed region just above the ash. As this carbon dioxide is drawn up through the middle region of the fuel bed by the action of draft, it unites with more carbon to form

carbon monoxide ($CO_2 + C = 2CO$). This process of reducing CO_2 to CO is called reduction, and the middle region of the fuel bed where this action takes place is known as the "reducing zone."

When the carbon monoxide leaves the fuel bed, it combines with the oxygen from the air being supplied through the firing door and burns to carbon dioxide ($2CO + O_2 = 2CO_2$).

Hence the zones in a fuel bed going from the bottom to the top are:

(1) Ash Zone.
(2) Oxidation Zone, where C is burned to CO_2.
(3) Reducing Zone, where CO_2 is reduced to CO.
(4) Distilling Zone, where the volatile matter and moisture of the fresh coal are distilled off.

In order to maintain the foregoing processes of perfect combustion, it is essential that the three following conditions be accomplished:

(1) Maintain a sufficient supply of air both above and below the fuel bed.
(2) Produce a thorough mixing of the supply air with the combustible gases.
(3) Maintain a sufficiently high temperature to support combustion.

128. Flue Gases.—*Flue gases are the products of combustion from the fuel bed of the furnace which pass up the stack or chimney.* The constituents of the flue gas depend on the kind of fuel burned and the completeness of combustion. The usual products contained in the flue gas when coal is burned are: carbon dioxide, CO_2; carbon monoxide, CO; nitrogen, N_2; oxygen, O_2; sulphur dioxide, SO_2; smoke, unburned hydrocarbons, and water vapor. If the combustion in the furnace is complete, there will be no carbon monoxide, unburned hydrocarbons, or carbon particles in the flue gas.

129. Flue Gas Analysis.—A flue-gas analysis usually determines the percentage by volume of carbon dioxide, carbon monoxide, and oxygen; the percentage of nitrogen is determined by difference.

An instrument commonly employed for this purpose is the **Orsat apparatus,** which is illustrated in Fig. 51. It contains three pipettes, *A*, *B*, and *C*, which are filled respectively with caustic potash, an alkaline solution of pyrogallol, and an acid solution of cuprous chloride. A measuring burette and a displacement bottle are also provided.

A 100-cc sample of the flue gas is drawn into the burette through the gas filter which is filled with spun glass or similar material to clean the gas. To discharge any air from the apparatus, the cock *G* is opened to the air and the bottle *F* raised until the water in the burette reaches the 100-cc mark. The cock *G* is then turned so as to close the air opening and allow the flue gas to be drawn through the filter, the bottle *F* being lowered for this purpose. The gas is drawn into the burette to a point below the zero mark; the cock *G* is then opened to the air so as to expel the flue gas until the water in the burette rises to the zero mark. We are now ready to conduct an analysis of the 100-cc gas sample contained in the burette.

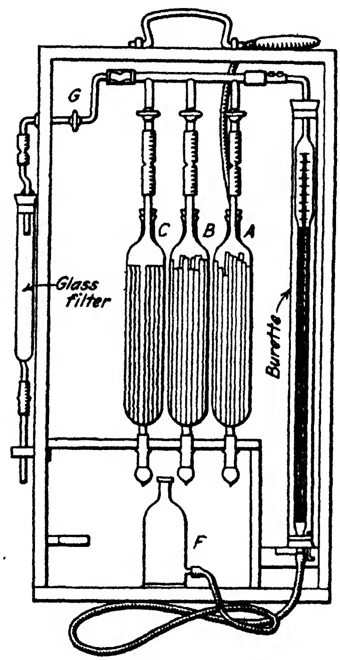


Fig. 51.—Orsat apparatus.

The cock to the first pipette *A* is opened and the water bottle raised so as to force the gas into this pipette. After several minutes the gas is drawn back into the burette by lowering the water bottle to its original position. The difference in the reading of the gas volume contained in the burette is the percentage of carbon dioxide in the sample. The remaining gas is treated in a similar manner in pipettes *B* and *C* where the oxygen and carbon monoxide are removed. The shrinkage in volume of the sample after being in any one of the pipettes gives the percentage by volume of the gas absorbed in that pipette. It should be remem-

bered that pipette *A* absorbs carbon dioxide, *B* absorbs oxygen, and *C* absorbs carbon monoxide. The volume of the gas that is left after being passed through each of these three pipettes is the percentage of nitrogen.

The sample of flue gas is usually taken at a point in the breeching where the products of combustion are just leaving the boiler.

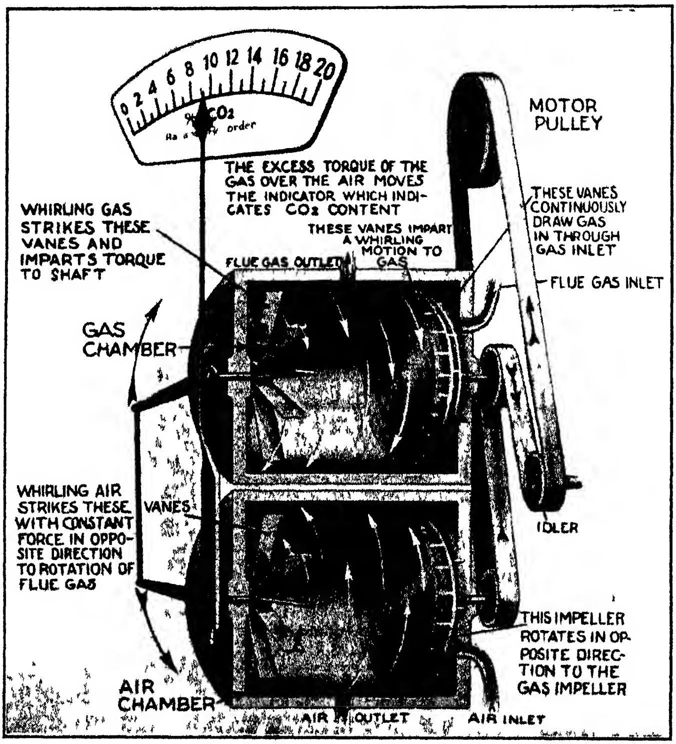


FIG. 52.—Sectional view of a Ranarex CO_2 recorder.

130. Ranarex Carbon Dioxide Recorder.—Fig. 52 shows a Ranarex carbon dioxide indicator and recorder which is used to indicate the percentage of carbon dioxide present in the flue gases leaving the boiler outlet. The operation of this instrument is based on the fact that the density of the flue gas increases in proportion to its carbon dioxide content, being about 50 percent heavier than the other constituents of flue gas.

During operation, flue gas is continuously drawn from the base of the chimney and passed into a small cylindrical chamber of the instrument. Upon entering this chamber the gas is given a rotary motion by means of a motor-driven impeller running in the chamber. This impeller drives the flue gas against the blades of an impulse wheel located at the other end of the chamber, and thus produces a twisting effect or torque on the shaft of this impulse wheel, this torque being proportional to the carbon dioxide content of the flue gas.

Located directly below this flue gas chamber is a second chamber of similar design into which air is supplied instead of flue gas. A rotating impeller causes a whirling of the air within the chamber, driving it against a second impulse wheel, thus producing a torque on the shaft of this wheel. However, this second torque is in the opposite direction to that of the impulse wheel shaft driven by the flue gas. The two impulse wheel shafts are coupled together by means of two levers and a connecting link. This coupling system prevents complete rotation of the wheels, but the difference in the magnitude of the two opposing torques causes a limited motion of the system. This movement is transmitted to a pointer designating the figures on the scale of the instrument calibrated in terms of carbon dioxide content of the flue gas.

131. Interpretation of Results of a Flue Gas Analysis.—A flue-gas analysis showing about 1 percent of carbon dioxide for every 4 percent of nitrogen is an indication that the process of combustion in the furnace is taking place under very favorable conditions. A lower percentage of carbon dioxide than this indicates that an excess of air is being supplied to the fire. This excess of air may not be under the immediate control of the fireman since it may be getting into the furnace through leaks in the boiler setting. If the analysis shows too large a percentage of oxygen it is also an indication that too large a quantity of air is being supplied to the fire.

A typical flue-gas analysis from a horizontal return tubular boiler is as follows:

Carbon dioxide	= 13.5 percent
Carbon monoxide	= 0.1 percent
Oxygen	= 5.9 percent
Nitrogen	= 80.5 percent

Flue-gas analyses within the following ranges indicate normal furnace conditions:

Carbon dioxide	= 10 to 4 percent
Carbon monoxide	= None
Oxygen	= 4 to 8 percent
Nitrogen	= 78 to 86 percent

132. Fuels for Power Purposes. *Anthracite.*—Anthracite is a very hard, black coal which consists largely of carbon. It is very difficult to ignite, burns with a small flame since it has a small percentage of volatile matter, and produces an intense heat with little or no smoke.

TABLE XII

ANTHRACITE COAL SIZES

Trade Name	Size of Opening	
	Through Inches	Over Inches
Broken	$4\frac{1}{2}$	$3\frac{1}{4}$
Egg	$3\frac{1}{4}$	$2\frac{5}{16}$
Stove	$2\frac{5}{16}$	$1\frac{5}{8}$
Chestnut	$1\frac{5}{8}$	$\frac{7}{8}$
Pea	$\frac{7}{8}$	$\frac{9}{16}$
No 1 Buckwheat	$\frac{9}{16}$	$\frac{5}{16}$
No. 2 Buckwheat or Rice	$\frac{5}{16}$	$\frac{3}{16}$
No. 3 Buckwheat or Barley	$\frac{3}{16}$	$\frac{3}{32}$
Culm	$\frac{3}{32}$	

Table XII gives the names and sizes of anthracite coal as it is usually marketed. The larger sizes of anthracite are seldom employed for power-plant purposes because of their high price. When anthracite is used in commercial plants it is usually of the Nos. 1, 2, and 3 buckwheat variety. In plants where the finer hard coal is used, a small percentage of bituminous coal, say 10 percent, is sometimes mixed with the anthracite.

Semi-Anthracite.—Semi-anthracite is a hard coal, but it is somewhat lighter and softer than anthracite. It contains a lower

percentage of carbon than anthracite and a higher percentage of volatile matter. As a result of its higher percentage of volatile matter, this coal burns with a longer and more luminous flame than pure anthracite, and also ignites more readily and makes an intense free-burning fire.

This coal is available in but limited quantities in the United States, which is unfortunate since it is one of the best steam-generating coals.

Semi-Bituminous.—Semi-bituminous coal is softer than the anthracites, having a lower density and a higher percentage of volatile matter. It ignites readily and burns with a small amount of smoke. This coal is commonly used for power-plant purposes.

Bituminous Coal.—Bituminous coal is a soft coal having a color ranging from a jet-black to a deep brown. Bituminous coals usually contain 25 percent or more of volatile matter and less than 65 percent of fixed carbon. They are very brittle and break into small lumps when stored. The high percentage of volatile matter produces a long yellow flame, as well as a large amount of smoke. They also have the characteristic of absorbing moisture in large quantities.

A bituminous coal will kindle very readily; in some cases this is considered an undesirable feature since it is likely to ignite spontaneously unless stored under the proper conditions. However, in spite of these undesirable characteristics, bituminous coal is employed extensively for commercial power generation, and it finds a large usage in the field of the manufacture of coke and artificial gas.

As the variation in character of bituminous coals is much greater than that of the anthracites, no classification as to size holds good in all localities. Table XIII gives the names and sizes of various bituminous coals.

Cannel Coal.—Cannel coal is a low-carbon bituminous coal which contains a very high percentage of volatile matter. It has a grayish-black color, kindles readily, and burns with a heavy black smoke. It is seldom used for power-plant purposes, but finds its chief usage in the manufacture of artificial gas. It is also frequently used in home fireplaces.

Lignite.—Lignite is a solid fuel which has a deep brown color and a wood-fiber structure. It contains an extremely large

Table XIII

NAMES AND SIZES OF BITUMINOUS OR SOFT COAL

Name	Will Pass through	Will Not Pass through
Duff	$\frac{1}{8}$-in. screen	and smaller
No. 3 Nut	$1\frac{1}{4}$-in. "	$\frac{3}{4}$-in. screen
No. 2 Nut	2-in. "	$1\frac{1}{4}$-in. "
No. 1 Domestic Nut	3-in. "	$1\frac{1}{2}$-in. "
No. 4 Washed	$\frac{3}{4}$-in. "	$\frac{1}{4}$-in. "
No. 2 Washed Stove	2-in. "	$1\frac{1}{4}$-in. "
No. 1 Washed Egg	3-in. "	2-in. "
No. 3 Roller Screened Nut	$1\frac{1}{2}$-in. "	1-in. "
No. 2 Roller Screened Nut	2-in. "	$1\frac{1}{2}$-in. "
No. 1 Roller Screened Nut	$3\frac{1}{2}$-in. "	2-in. "
Egg	6-in. "	3-in. "
Lump or Block	6-in. " and over	
Run of Mine	Unscreened	
Domestic By-product Coke		
Egg	3-in screen	$2\frac{1}{2}$-in. screen
Large Stove	$2\frac{1}{2}$-in. "	2-in. "
Small Stove	2-in. "	$1\frac{1}{2}$-in. "
Nut	$1\frac{1}{2}$-in. "	$\frac{3}{4}$-in. "
Pea	$\frac{3}{4}$-in. "	$\frac{1}{2}$-in. "

portion of volatile matter with a correspondingly small amount of fixed carbon. It kindles easily and burns with a yellow flame, but it cannot be stored for long periods of time since it crumbles readily when exposed to air. Lignite is often described as a coal in its early stages of formation.

Peat.—Peat is composed essentially of decayed vegetable matter such as plants, mosses, ferns, etc. It has a fibrous structure and contains such large percentages of moisture that it must be dried before using.

133. Selection of a Coal for Industrial Use.—The selection of a solid fuel for industrial use may be narrowed down to the choice of a suitable coal. If waste products such as sugar-cane, sawdust, and the like are available, they may be burned as fuel, but coal is the principal industrial fuel in this country.

In making the choice of a coal four factors should generally be considered. They are:

1. *Availability of supply.*
2. *Continuity or dependability of supply.*
3. *Cost.*
4. *Character and composition of coal.*

A brief consideration of the location of the plant with reference to nearby coal fields will soon determine which coal will be available without the introduction of prohibitive transportation costs. If the plant is located in the eastern part of the United States, there will be a great variety of coals from which to make a selection. However, if the plant is located inland, the selection of a coal will be more restricted, and in some places only one coal may be available.

A second consideration is the dependability of the supply, that is, whether the plant may be assured of a continuous supply of the selected coal. This is an important factor, since the burning characteristics of coals differ greatly and the operating crew must learn the adjustment of the burning equipment for each particular coal. The frequent changing of coals often results in a very distinct loss of money to the plant.

The third, and perhaps the deciding, factor in most cases is cost. The usual method of considering the cost of a coal is on the Btu per dollar basis, that is, the number of Btu that are obtained for the expenditure of one dollar. Since the "combustible" (carbon, hydrogen, and sulphur) is the heat-producing part of the coal, the cost of a ton of moisture- and ash-free coal is also a fair basis for comparison.

For example, let us suppose that a coal has a heating value of 15,500 Btu per lb on an "as received" analysis. To convert this to a heating value on a "combustible" basis, it is necessary to have a knowledge of the total percentage of ash and moisture in the coal. Let us assume this to be 12 percent. The heating value on a moisture- and ash-free basis would be $15{,}500 \div (1.00 - 0.12) = 17{,}600$ Btu per lb. This represents the heat that would be generated by burning one pound of the coal if it contained no ash or moisture.

The fourth factor to be considered in the selection of a coal for industrial purposes is its chemical composition and physical

properties. The factors that indicate the heat available in a certain coal are included almost entirely in its chemical analysis. However, thought should also be given to its physical properties, which determine to a great extent the amount of this available heat that may be absorbed by the boiler. Thus it is important to study its behavior on the grate: whether or not it cakes, fuses, slacks, or burns freely when heated.

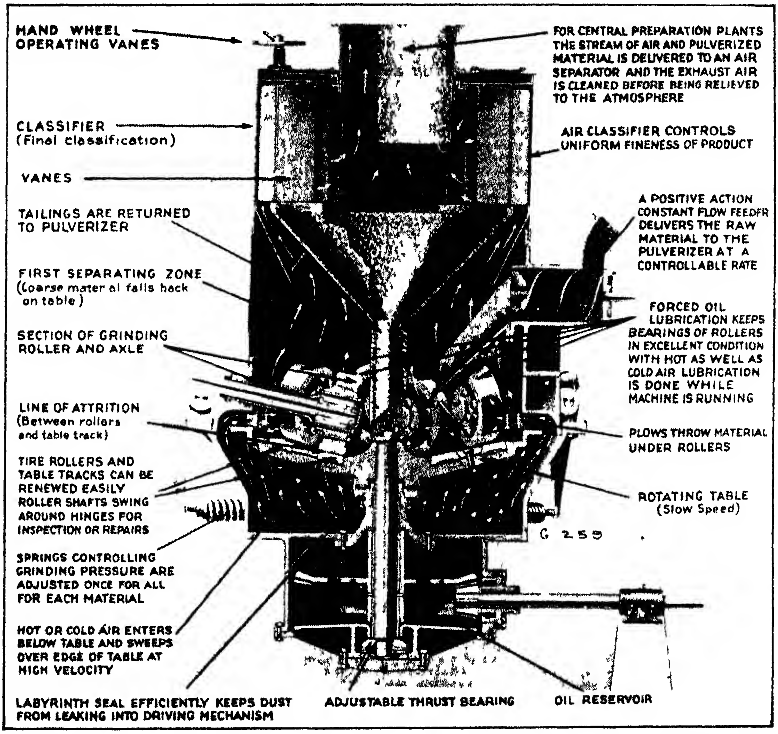
The percentage of ash in coal is important, not only as to its amount, but also as to its fusibility. A large amount of ash will cause difficulty in burning the coal, and a low-fusing ash will offer difficulty in removal from the furnace. Generally speaking, therefore, it is safe to say that the lower the percentage of ash, the better will be the coal for power-plant use. It is also safe to conclude that, the higher the fusing temperature of the ash, the more desirable will be the coal for burning in all types of furnaces. Ash with a low fusing temperature fuses on the grate and makes a troublesome clinker which may seriously interfere with the burning of the coal by closing the air spaces in the grate bars.

Moisture is also an undesirable ingredient in coal since it is always a direct loss to the buyer. He must pay freight charges for transporting this moisture and also suffer losses during its evaporation in the furnace. If the moisture is excessive, the coal will pack and offer considerable difficulty in flowing from the coal bunkers to the furnace. This is particularly true if the coal is fine, as it frequently is in stoker-fired plants.

Carbon and hydrogen constitute the combustible portion of coal. The heating value of a coal is almost entirely dependent upon the amount of carbon and available hydrogen present. (Available hydrogen is that which is not combined with oxygen in the form of water.) Carbon and hydrogen exist in coal in definite proportions according to the geologic age of the coal. This carbon-hydrogen ratio has often been proposed as a means of classification of coal. It varies from 30 for anthracite to 10 for lignite.

Sulphur is considered an undesirable element in coal. It is usually combined with iron as pyrites and is a source of clinker formation in the furnace. The products of combustion of sulphur are often the cause of excessive corrosion of boiler tubes, economizers, and air preheaters. The sulphur dioxide combines with water during the combustion and forms sulphuric acid, which will attack metallic parts and corrode them very quickly.

134. Pulverized Coal.—Pulverized coal is usually powdered to such a fineness that 65 percent will pass through a 200-mesh screen and all of it through a 20-mesh screen. Sometimes it is specified that 80 percent shall pass through a 200-mesh screen. When coal is powdered in this form it is similar to a dust and will float in air.



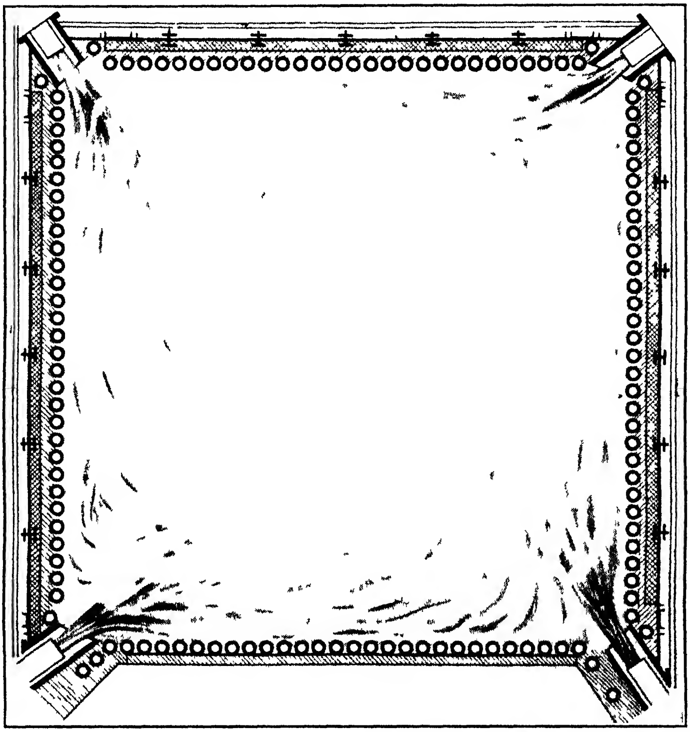
(Courtesy of Grindle Fuel Equip Co.)

Fig. 53.—Coal Pulverizer.

Fig. 53 gives a cross-sectional view of a typical roller type of coal pulverizer. Before the coal is fed to the pulverizer, it is first crushed so that no piece is larger than one inch in diameter, and the moisture is also removed by a suitable drying process.

The dry coal, which is crushed to size, is fed onto the slowly revolving grinding table of the pulverizer by means of a variable-speed feeding screw. Here it is reduced to a fine powder by the

action of large rollers. Air moving with a high velocity sweeps across the grinding table from the edge toward the center and ultimately passes up through the vanes at the top of the pulverizer and out into the delivery pipe. This rapidly moving current of air picks up any pulverized coal dust that is on the table and carries it along to the delivery pipe, whence it is fed directly to the furnace.



(*Courtesy of Combustion Engrg Corp.*)

FIG. 54.—Plan view of tangentially fired pulverized coal furnace.

The tailings, or heavy particles of coal dust, drop back on the grinding table to be further pulverized.

This finely divided coal dust, along with a suitable amount of air, is fed into the furnace through nozzles located in the corners of the furnace. A plan view of the action of the combustion flame is pictured in Fig. 54. The burning is accompanied with a cyclonic action and turbulence which result in a flame that almost entirely fills the furnace.

The following table contrasts the advantages and the disadvantages in the use of pulverized coal.

ADVANTAGES AND DISADVANTAGES IN THE USE OF PULVERIZED COAL

Advantages	Disadvantages
More perfect combustion	Danger of spontaneous ignition or explosion
Minimum of smoke	Difficulty of pulverizing coal to uniform size
Less ash to remove	Impracticability of applying to small plants
Less expensive coal may be burned	
Cleaner working conditions	
Flexible system of control	
Reduction in operation costs	

135. Briquetted Coal.—Briquetted coal is essentially a finely powdered coal which is pressed into briquettes, the coal being held together by a binder such as pitch. A briquetted coal possesses the desirable characteristics of reducing the loss of fuel through the grates, increasing the total available heat content of the coal, permitting the burning of lower grades of coal, and permitting the handling and weathering of slacking coals without disintegration.

136. Weathering of Coal.—Irregularities in transportation facilities necessitate that large plants keep an adequate store of coal on hand at all times. Anthracite is an easily stored coal since it may be piled in an almost unlimited amount without danger of spontaneous ignition. With bituminous coals, however, the case is quite different. Most bituminous coals will spontaneously ignite if stored in large piles, as well as suffer from disintegration. Spontaneous combustion can take place, however, only when the air supply will produce rapid oxidation and cannot carry away the heat generated. If a careful record is kept of the temperature of the coal at various parts of the coal pile, it is possible to detect regions of trouble and shift the pile before a large loss is realized.

It is found that all coals lose heat during storage in the open air, but this loss is of small significance in comparison with the loss due to disintegration and spontaneous ignition. Storage of the coal under water will reduce all these losses to a minimum.

137. Wood as a Fuel.—Wood is a vegetable tissue containing from 30 to 50 percent of moisture. This moisture content may be reduced to 18 to 20 percent by drying the wood in the atmosphere for a period of approximately one year. Woods are usually classified as soft or hard, e.g.:

Soft Woods	Hard Woods	Soft Woods	Hard Woods
Pine	Oak	Willow	Birch
Fir	Walnut	Poplar	Hickory
Elm	Maple	Chestnut	
Spruce	Beech		

138. Heating Value of Wood.—Theoretically, equal weights of wood substances should evolve equal quantities of heat when completely burned. In practice, however, this is not true, owing to variations in the structure of the wood tissues; presence of varying amounts of rosin, gum, oil, etc.; and particularly to differences in the ease with which combustion can be accomplished. A variation in the percentage of rosin may change the heating value of the wood as much as 12 percent. Contrary to general belief, the heating value per pound of most soft woods will be found to be slightly greater than that of hard woods. Table XIV

TABLE XIV

ULTIMATE ANALYSES AND HEATING VALUES OF DRY WOODS

(Gottlieb)

Kind of Wood	C	H	N	O	Ash	Btu per Pound
Oak	50.16	6 02	0.09	43.36	0.37	8316
Ash	49 18	6.27	0.07	43.91	0.57	8480
Elm	48.99	6.20	0 06	44.25	0.50	8510
Beech	49.06	6.11	0.09	44.17	0.57	8591
Birch	48.88	6.06	0.10	44.67	0.29	8586
Fir	50.36	5.92	0.05	43.39	0.28	9063
Pine	50.31	6.20	0.04	43.08	0.37	9153
Poplar	49.37	6.21	0.96	41.60	1.86	7834*
Willow	49.96	5.96	0.96	39.56	3.37	7926*

* Btu calculated.

gives the chemical composition and the heating value of a few of the more common woods.

It should be noticed that the heating values as reported in Table XIV are on a dry basis. If any of these woods are used for steaming purposes, it will be found that the quantity of heat available will be less than the amount reported in this table, since a portion of this heat will be required to evaporate the water contained in the wood.

139. Liquid Fuels.—Crude petroleum is the only liquid fuel of sufficient abundance to be used commercially. It is considered to be of organic origin, and is probably the result of decomposition of animal, vegetable, and mineral material.

Crude oil may be roughly divided into three classes in accordance with the nature of the residue after distillation. They are as follows:

(1) *Paraffin Base*, which includes the lighter oils.
(2) *Asphalt Base*, which ordinarily contains the heavier-grade oils.
(3) *Mixed Base*, which contains varying proportions of paraffin and asphaltic bases. This class forms the large group of intermediate-grade oils.

Although oil may be found in almost every portion of the world, the principal supplies available at the present time are from the United States, Mexico, and Russia.

140. Chemical Composition and Heating Value of Crude Oil.—Liquid fuels are composed of carbon, hydrogen, oxygen, nitrogen, sulphur, silt, and moisture. The carbon and hydrogen form the principal constituents in the form of hydrocarbons. The heating value ranges from 17,000 to 20,000 Btu per lb, although the ordinary grades available for fuel purposes have a heating value from 17,500 to 19,000 Btu per lb.

Table XV gives typical analyses together with their value for several fuel oils.

141. Physical Properties of Crude Oil.—When liquid fuels are used for power purposes, certain physical characteristics should be considered in determining the suitability of the available supply. They are as follows:

(1) *Specific gravity* is the ratio of the weight of a given volume of oil to that of an equal volume of water. In general, it may be

TABLE XV

CHEMICAL COMPOSITION AND HEATING VALUE OF VARIOUS CRUDE OILS

Kind of Oil	C	H	S	O	Deg Fahr. Flash Point	Specific Gravity	Btu per Pound
California	81.52	11.51	0.55	6 92	230	0 94	18,667
Texas	83.30	12.40	0.50	3 83	216	0.93	19,481
Ohio	83.40	14.70	0.60	1.30	...	....	19,580
Pennsylvania	84.90	13.70	....	1.40	...	0.89	19,210
West Virginia	84.30	14.10	....	1.60	...	0.84	21,240
Russia	86.60	12.30	....	1.10	...	0.94	20,138

said that the higher the specific gravity of the oil, the lower will be its heating value, and vice versa. This is true since the heavier oils contain a smaller percentage of hydrocarbons than the lighter oils. The heavier oils have a lower heating value per pound, but they take up less storage space because of their greater density.

Specific gravity of liquid fuels is ordinarily expressed by a direct reading of the Baumé hydrometer, the specific gravity being recorded in **degrees Baumé.** The hydrometer is so constructed that the heavier oils bear smaller Baumé readings than the lighter oils. Fig. 55 gives an approximate heating value for fuel oils of different Baumé specific gravities.

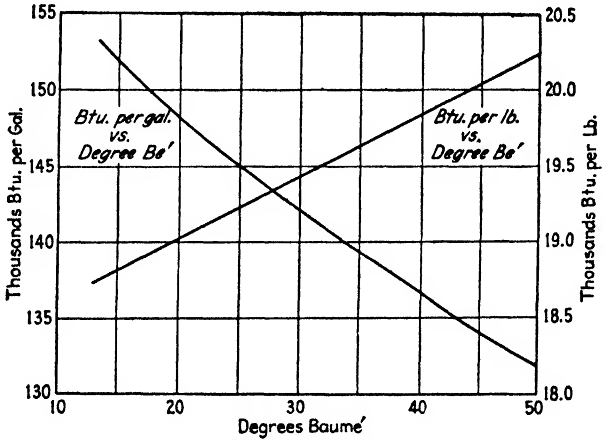
(2) *Flash point.*—The flash point is the temperature at which an inflammable mixture of gases is driven from the oil when it is heated. If the oil is heated in an open vessel and the distilled vapors constantly tested with an electric spark, it will be found that they will ignite when the oil is heated to a certain definite temperature. This temperature is the flash point of the oil.

If the vapors are distilled off in a closed cup it will be found that ignition takes place at a lower temperature than before. This is known as the " closed cup " flash point; the former method gives the " open cup " flash point. Most insurance companies require a minimum of 150 deg fahr " closed cup " flash point for oil that is to be stored.

(3) *Viscosity* designates the resistance of oil to flow; it is due

to the internal friction of a liquid. The viscosity of any oil will change with changes in temperature, becoming lower at higher temperatures. In order to set a standard for the determination of relative viscosities of different fuel oils, a temperature of 60 deg fahr has been selected as a basis for comparison.

(4) *Specific Heat.*—The specific heat of fuel oil will be found to vary with the chemical composition, being higher as the hydrogen content is greater and lower as the carbon content is greater. The range of specific heat is from 0.4 for California oils to 0.5 for the Pennsylvania crudes.



(*Courtesy Lennox Furnace Co.*)

FIG. 55.—Approximate heating value of fuel oils.

142. Saybolt Viscosimeter.—Viscosity is usually determined by finding the time in seconds required for a definite quantity of the liquid to flow through an orifice of standard diameter and length. The instrument used in determining this property is known as a **viscosimeter,** one type of which is shown in Fig. 56.

In the standard instrument used in determining the viscosity of lubricating oils, the oil to be tested is placed in a chamber having about 83 cc capacity. At the bottom of the oil chamber is an orifice 9 mm in length and 1.6 mm in internal diameter. This oil chamber is surrounded by a water bath which is kept at a constant temperature by means of an electric heating device, or by passing steam through a steam heating coil which is provided.

Thermometers are immersed in both the oil to be tested and the water bath surrounding the oil chamber.

The viscosity is determined by noting the time in seconds required for 60 cc of oil to flow through the orifice. For water at 70 deg fahr this is 30 sec in a standard instrument. Saybolt

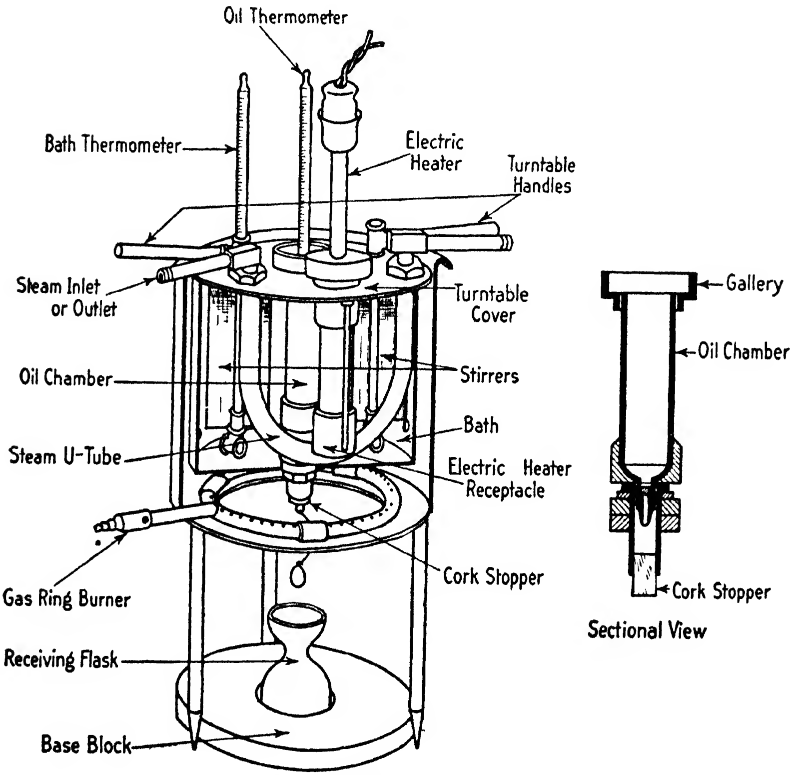


FIG. 56.—Saybolt viscosimeter.

viscosity tests are generally conducted at the following temperatures:

210 deg fahr for heavy oils of the 600-W class.
100 deg fahr for engine and machine oils.
100 deg fahr for lubricating oils for internal-combustion engines.

143. Gaseous Fuels.—Blast-furnace gas, natural gas, illuminating gas, and by-product coke-oven gas are the principal gaseous fuels.

Blast-furnace gas is a by-product of the blast furnace used to melt iron ore. Its principal constituents are: carbon dioxide, 10.0 percent; carbon monoxide, 27.4 percent; hydrogen, 3.6 percent, and nitrogen, 59.0 percent. The gas usually contains about 25 to 50 grains of moisture per cubic foot, this moisture being picked up during its progress through the furnace. The heating value varies from 85 to 100 Btu per cu ft, depending for the most part on the percentage of carbon dioxide present.

The volume of gas produced per ton of iron melted varies between 133,000 and 150,000 cu ft.

Natural gas is a natural product which is obtained from the earth. It is not a common power fuel since its use is to a great extent limited to the communities where it is available. The heating value of natural gas is considerably higher than that of blast-furnace gas because of its higher hydrocarbon content. An average heating value will vary from 900 to 1100 Btu per cu ft. A typical analysis of an Indiana natural gas gives the following composition: hydrogen, 1.86 percent; methane, 93.07 percent; carbon monoxide, 0.73 percent; carbon dioxide, 0.26 percent; nitrogen, 3.02 percent; oxygen, 0.42 percent, and heavy hydrocarbons and sulphur 0.62 percent.

Coke-oven gas is the product of destructive distillation of coal in a coking oven. The volatile gases driven off during the process of manufacturing coke are collected and cooled, and such by-products as tar, crude naphthalene, ammonia, and benzol are removed. The average composition of coke-oven gas is: carbon dioxide, 0.80 percent; oxygen, 1.6 percent; carbon monoxide, 4.9 percent; methane, 28.4 percent; hydrogen, 54.2 percent; nitrogen, 10.1 percent. Its heating value varies from 460 to 550 Btu per cu ft.

Illuminating gas is essentially a mixture of carbon monoxide and hydrogen. It is formed by passing superheated steam over very hot anthracite coal or coke. In this process the oxygen of the water combines with carbon from the coal to form carbon monoxide and leaves the hydrogen from the water in the free state. In order to use this gas for illuminating purposes, so-called "illuminants" are added. These illuminants are usually hydrocarbonous

gases from oil or naphtha. This gas finds its principal use for lighting and cooking purposes in the home.

144. Heating Value of Gaseous Fuels.—The heating value of gaseous fuels is usually determined by means of a **Junker calorimeter** such as represented in Fig. 57. The gas whose heating value is to be determined is burned at a constant rate within a nearly

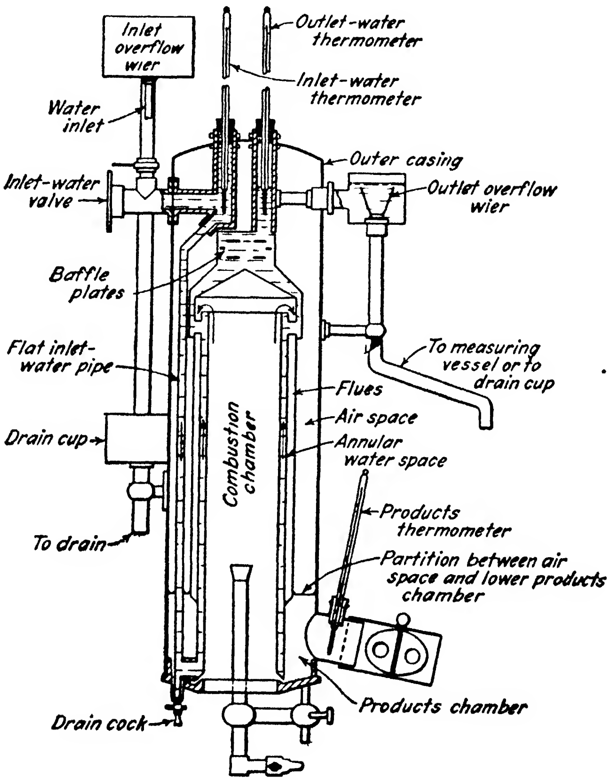


Fig. 57.—Junker calorimeter.

closed chamber, called the combustion chamber. The air necessary to support combustion enters the combustion chamber through the open bottom of the calorimeter, the circulation through the instrument being induced by the heated products of combustion. The heated gases pass up through the combustion chamber, which is surrounded by flowing water, then downward through tubes or spaces which are also water-cooled, and finally are dis-

charged to the atmosphere through an outlet in which there is a damper to regulate the rate of flow of these gases.

The quantity of gas used is measured by a gas meter, and the water used during a test is collected and weighed. The temperature of the inlet and outlet water is observed by the thermometers. The heating value of the gas is found by multiplying the weight of the water in pounds by the rise in temperature in degrees Fahrenheit and dividing this product by the volume of the gas used during the test. This volume should be measured in cubic feet.

It is customary to express the heating value of a gas for conditions of 60 deg fahr and a normal atmospheric pressure of 29.92 in. of mercury. In order to do this the heating value as obtained above is reduced to an equivalent heating value for these standard conditions of pressure and temperature by means of the equation

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

This equation is used to find the equivalent volume of gas for the standard condition.

SUMMARY OF CHAPTER VII

FUELS are substances which will burn and give off stored or fixed energy in the form of heat energy.

A PROXIMATE ANALYSIS of a fuel shows the percentage by weight of moisture, fixed carbon, volatile matter, ash, and sulphur in the fuel.

An ULTIMATE ANALYSIS shows the percentage by weight of each of the principal elements in a fuel.

COMBUSTION is defined as any process of burning which evolves heat. Oxygen supports combustion; that is, in order for a fuel to burn it must be in the gaseous form and in combination with sufficient oxygen, and must be at a temperature above that of its kindling point.

The three essentials to perfect combustion of a fuel are:

(1) Sufficiently high temperature to maintain combustion.
(2) Ample supply of oxygen (usually from the air).
(3) Thorough mixing of the air and gases.

The HEATING VALUE of a solid fuel may be calculated from the following equation:

$$\mathbf{H = 14{,}600C + 62{,}000(H - O/8) + 4000S}$$

where H = the heating value of the fuel in Btu per lb, and C, H, O, and S the respective percentages by weight of carbon, hydrogen, oxygen, and sulphur in the fuel.

The THEORETICAL AMOUNT OF AIR required for combustion may be determined by the following formula:

$$\text{Pounds of air per pound of coal} = 11.6C + 34.8(H - O/8) + 4.35S$$

The PRODUCTS OF COMBUSTION are those substances which are driven off during the burning of a fuel. The usual ones are carbon dioxide, carbon monoxide, oxygen, and nitrogen. Most of these are carried away from the fuel in gaseous form, and are known as FLUE GASES. An analysis of the constituents of flue gas may be made with an Orsat apparatus.

REVIEW PROBLEMS ON CHAPTER VII

1. What are the constituents of coal as disclosed by a proximate analysis? Explain the process of determining each item.

2. For an Eastern grade of bituminous coal, what are the approximate percentages of the items in a proximate analysis?

3. What are the elements of coal as disclosed by an ultimate analysis?

4. Write a typical ultimate analysis for a Pennsylvania anthracite.

5. State three bases for reporting a coal analysis.

6. An ultimate analysis of an Alabama coal gave the following results: carbon, 72.02; hydrogen, 4.78; oxygen, 6.45; nitrogen, 1.66; sulphur, 0.80; ash, 14.29. Determine both the heating value of the coal and the number of pounds of air required for perfect combustion per pound of coal.

7. A West Virginia coal from Rush Run Mine yielded the following ultimate analysis: carbon, 83.71; hydrogen, 4.64; oxygen, 3.67; nitrogen, 1.70; sulphur, 0.71; ash, 5.57. Calculate the heating value of this coal. If this coal is burned with 60 percent excess air, how many pounds of air is supplied per ton of coal?

8. An Illinois coal has a heating value of 13,200 Btu per lb on an "as fired" basis. If the coal contains 8.3 percent moisture and 10.5 percent ash, determine the heating value on a "moisture-free basis" and on a "combustible" basis.

9. Explain the process of pulverizing coal. State the advantages and disadvantages of its use.

10. What is the significance of the term "fusing point of the ash"?

11. State the physical properties of peat, lignite, cannel coal, blast-furnace gas, and illuminating gas.

CHAPTER VIII

PROPERTIES OF AIR AND ITS MOISTURE CONTENT

145. Composition of Air.—Air is composed essentially of a mechanical mixture of several gases. The chief constituents are oxygen and nitrogen, but small percentages of carbon dioxide and water vapor and extremely small portions of inert gases are also present, to say nothing of dust. Ordinary pure dry air has the following composition, in percentages:

	By Volume	By Weight
Oxygen................	20.9	23.1
Nitrogen..............	79.1	76.9

The specific density of air, that is its weight per cubic foot, decreases with an increase of temperature, provided the pressure remains constant. Since the density of air varies with both the temperature and pressure, it is necessary, in order that there may be a suitable basis for comparison, that all densities be referred to some standard set of conditions. The condition now generally accepted as standard for air as well as for all other gases is a pressure of 14.7 lb. per sq in. and a temperature of 32 deg fahr.

Tables XVI and XVII give the properties of dry air and saturated air at atmospheric pressure for various temperatures.

146. Specific Heat of Air.—Air, like all other gases, has a specific heat for conditions of constant volume, S_v, and a specific heat for conditions of constant pressure, S_p.

147. Specific Heat at Constant Volume.—The *specific heat of a gas confined at constant volume,* S_v, *is the quantity of heat required to raise the temperature of one pound of the gas one degree Fahrenheit without a change in volume.* For example, if one pound of air were confined in a closed tank in such a manner that its volume could not change, the quantity of heat necessary to raise its temperature one degree Fahrenheit would be known as the specific heat of air at constant volume.

Table XVI

PROPERTIES OF DRY AIR BAROMETRIC PRESSURE 29.921 IN.

Temperature, deg fahr	Weight per cu ft, lb	Percent of volume at 70 deg fahr	Btu absorbed by 1 cu ft dry air per deg fahr	Cu ft dry air warmed one degree per Btu
0	0.08636	0.8680	0.02080	48.08
5	.08544	.8772	.02060	48.55
10	.08453	.8867	.02039	49.05
15	.08363	.8962	.02018	49.56
20	.08276	.9057	.01998	50.05
25	.08190	.9152	.01977	50.58
30	.08107	.9246	.01957	51.10
35	.08025	.9340	.01938	51.60
40	.07945	.9434	.01919	52.11
45	.07866	.9530	.01900	52.64
50	.07788	.9624	.01881	53.17
55	.07713	.9718	.01863	53.68
60	.07640	.9811	.01846	54.18
65	.07567	.9905	.01829	54.68
70	.07495	1.0000	.01812	55.19
75	.07424	1.0095	.01795	55.72
80	.07356	1.0190	.01779	56.21
85	.07289	1.0283	.01763	56.72
90	.07222	1.0380	.01747	57.25
95	.07157	1.0472	.01732	57.74
100	.07093	1.0570	.01716	58.28
105	.07030	1.0660	.01702	58.76
110	.06968	1.0756	.01687	59.28
115	.06908	1.0850	.01673	59.78
120	.06848	1.0945	.01659	60.28
125	.06790	1.1040	.01645	60.79
130	.06732	1.1133	.01631	61.32
135	.06675	1.1230	.01618	61.81
140	.06620	1.1320	.01605	62.31
145	.06565	1.1417	.01592	62.82
150	.06510	1.1512	.01578	63 37
160	.06406	1.1700	.01554	64.35
170	.06304	1.1890	.01530	65.36
180	.06205	1.2080	.01506	66.40
190	.06110	1.2270	.01484	67.40
200	.06018	1.2455	.01462	68.41
220	.05840	1.2833	.01419	70.48
240	.05673	1.3212	.01380	72.46
300	.05225	1.4345	.01274	78.50
400	.04618	1.6230	.01130	88.50
500	.04138	1.8113	.01018	98.24
600	.03746	2.0010	.00923	108.35
1000	.02720	2.7560	.00680	147.07

Table XVII

PROPERTIES OF SATURATED AIR BAROMETRIC PRESSURE 29.921 IN.

Temperature, deg fahr	Weight in a Cubic Foot of Mixture		
	Weight of the dry air, lb	Weight of the vapor, lb	Total weight of the mixture, lb
0	0.08625	0.000069	0 08623
10	.08433	.000111	.08444
20	.08247	.000177	.08265
30	.08063	.000276	.08091
40	.07880	.000409	.07921
50	.07694	.000587	.07753
60	.07506	.000829	.07589
70	.07310	.001152	.07425
80	.07095	.001576	.07253
90	.06881	.002132	.07094
100	.06637	.002848	.06922
110	.06367	.003763	.06743
120	.06062	.004914	.06553
130	.05716	.006357	.06352
140	.05319	.008140	.06133
150	.04864	.010310	.05894
160	.04341	.012956	.05637
170	.03735	.016140	.05349
180	.03035	.019940	.05029
190	.02227	.024465	.04674
200	.01297	.029780	.04275

When heat is added to a gas kept at constant volume, the temperature and pressure of the gas both increase. The heat supplied serves to increase the velocity of the molecules of the gas. The increased frequency with which these molecules strike against the sides of the containing vessel accounts for the increase in pressure on the sides of the vessel. The increase in temperature in the case of a perfect gas would be directly proportional to the quantity of heat added. The heat capacity or specific heat of a gas at constant volume is a definite quantity for any gas and for any fixed range of temperature.

Table III on page 62 gives a set of values for the specific heat of the common gases at constant volume. The specific heat of

air at constant volume is given in this table as 0.1689 Btu per lb per deg fahr. This value may be safely used in most technical calculations without introducing any serious error.

148. Specific Heat at Constant Pressure.—The *specific heat of a gas held at constant pressure, S_p, is the quantity of heat required to raise the temperature of one pound of the gas one degree Fahrenheit without a change in pressure.*

When a gas is heated under conditions of constant volume all the heat supplied goes into internal energy of the gas, or, in other words, all the heat supplied produces an increase in temperature and pressure. However, when heat is applied to a gas which is maintained at a constant pressure, the volume of the gas must increase in order that the gas pressure shall not change. For an increase in volume to take place the atmosphere or other restraining body must be pushed back, and consequently work must be done against the opposing pressure which this body is exerting. This work is external work and does not produce an increase in temperature of the gas.

Thus when heat is added to air kept at constant pressure both the volume and temperature of the air increase. In this case not only must some **work** be done **externally** but also heat must be supplied to produce an increase in the molecular activity of the molecules of air in order to produce an increase in temperature. Since the air must be expanded as well as heated, *the specific heat of air at constant pressure will be larger than the specific heat of air at constant volume.* This fact is frequently written $(S_p - S_v) = R$; in which R represents the amount of external work done. R is expressed in Btu.

It is customary to use a constant value of 0.24 for the specific heat of air at constant pressure, regardless of the temperature of the air. The error arising from the use of this arbitrarily assumed constant value of the specific heat of air for conditions of constant pressure, particularly for moderate temperature ranges, is well within the limits of error encountered in technical heat calculations.

149. Dalton's Law.—An important conception that should be clearly understood is that air itself does not absorb moisture, but rather the molecules of water vapor are interspersed in the space unoccupied by the molecules of oxygen, nitrogen, etc. Thus a cubic foot of air containing moisture should be thought of as being composed of a mixture of molecules of oxygen, of nitrogen, and of

water vapor, all these molecules being widely scattered throughout the cubic foot of space.

If we neglect the minor constituents of air we might imagine the molecules of oxygen as being like blue marbles and the molecules of nitrogen as like red marbles. If we are to imagine a cubic foot of dry air at room temperature we must picture this cubic foot as containing a number of blue and red marbles dancing about at a very rapid rate. If, then, vapor is added, the picture is changed as if a number of rapidly moving white marbles were added.

A mechanical mixture of gases of this nature obeys a law known as **Dalton's law,** which states that *in a mixture of several gases at the same temperature each gas produces the same pressure as if the others were not there, and the total pressure is the sum of their separate pressures.*

In terms of the above illustration one may say that the striking of the red marbles on the sides of the container produces a definite pressure, the striking of the blue marbles produces a definite pressure, and likewise the white marbles produce a definite pressure, the total pressure against the sides being the sum of the three separate pressures.

To illustrate further the significance of this law, suppose we have a cubic foot of nitrogen at an absolute pressure of 10 lb per sq in. and we inject into this cubic foot space another cubic foot of hydrogen at an absolute pressure of 20 lb per sq in.; the result would be a cubic foot mixture of nitrogen and hydrogen under a pressure of $10 + 20 = 30$ lb per sq in. abs. Thus, considering the case of air, we see that the total barometric pressure equals the sum of the partial pressures of the oxygen, nitrogen, water vapor, and various other gases present.

150. Humidity.—**Absolute humidity** is the amount of moisture, or water vapor, mixed with the air in the atmosphere. The amount of moisture that any given volume of air can hold is *entirely dependent upon the temperature of the air.* As the temperature of air increases above freezing, its moisture-holding capacity increases very rapidly. The absolute humidity is often expressed in grains of moisture contained in one cubic foot of air, a grain being one seven-thousandth of a pound.

When air contains the maximum amount of moisture that it can hold at a given temperature without precipitation, it is said to

be **saturated,** or that the **relative humidity** is 100 percent. The temperature corresponding to saturation is known as the **dew point.** Air containing any amount of moisture can be cooled until the dew point is reached. At this temperature the moisture begins to precipitate out, forming a "dew." It is the cooling of air to the dew point that causes fog (small floating masses of liquid water); the moisture begins to precipitate out because the air is cooled until it can no longer contain the amount of moisture it held when it was warmer.

If at any given temperature air contains just one-half the weight of water vapor that it could contain when saturated, the air is said to have a relative humidity of 50 percent. In other words, *the term relative humidity expresses the ratio between the weight of water vapor that one cubic foot of air contains at a certain temperature and the weight of water vapor contained by one cubic foot of saturated air at this temperature.* Before discussing further the nature of humidity, dew, fog, etc., it may be well to refer to the practical importance of the subject.

151. Effect of Humidity on the Human Body.—The evaporation of moisture from the surface of the body helps, in hot weather, to maintain normal body temperature. The lower the relative humidity of the atmosphere the greater will be its capacity for picking up or evaporating water from the surface of the human body. When moisture is thus evaporated, heat is taken from the body by the process. When there is a high relative humidity and a high temperature, the evaporation from the body will be low, and the body, unable to give up moisture to the atmosphere, will feel hot and uncomfortable. A low relative humidity has the opposite effect; the evaporation is increased, and the body is called upon to supply an excessive amount of heat to produce this evaporation, the result being that a person feels chilly. Both of these cases might happen at exactly the same temperature, say 70 deg fahr. With the proper relative humidity a person can be perfectly comfortable at 70 deg fahr; but at a relative humidity between 10 percent and 20 percent one will feel chilly at this temperature.

The exact relative humidity for greatest comfort is an individual matter, but the *comfort limits are probably from 35 percent to 75 percent.* Low humidities are detrimental to health; they permit an increase of the dust content of the air which

carries bacteria, they dry out the mucous membranes of the nose and throat, reducing the natural protection against respiratory infection, and they irritate the nervous system by extreme dryness of the skin and by excessive evaporation.

Cold weather will cause a large amount of condensation to take place in a room where the walls are cold and the relative humidity is high. This condensation will occur on all surfaces that are cool enough to reduce the temperature of the contacting air down below the dew point.

Taking all factors into consideration, it is accepted practice to control the relative humidity for household purposes within the limits of 35 to 50 percent.

152. Measurement of Relative Humidity.—Direct determination of the amount of moisture in air at any time involves cumbersome and inconvenient experimental procedures. However, an indirect method of determining relative humidity, which is in common use, will be found to serve most practical purposes.

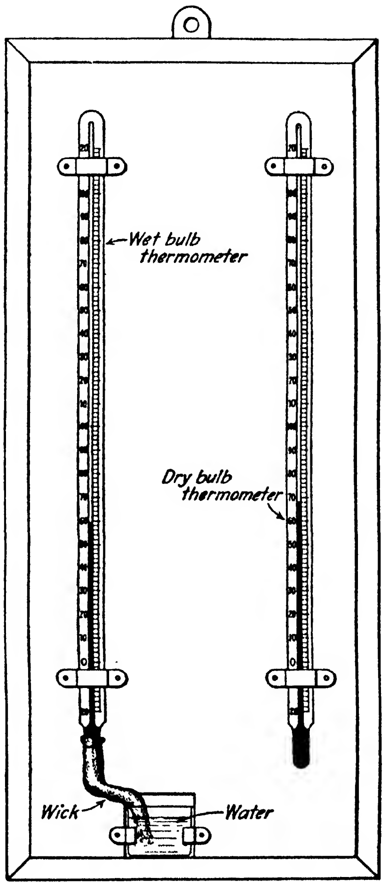


FIG. 58.—Wet-and-dry bulb hygrometer.

In its most common form the instrument used to determine relative humidity is the **wet- and dry-bulb hygrometer,** as shown in Fig. 58. This instrument is made of two accurate thermometers, one indicating the temperature of the air in the usual way, and the other having its bulb covered with a muslin wick which dips into a reservoir of water. This wick draws water up to the

one thermometer, keeping its bulb moist at all times. The evaporation of the water around this bulb lowers the temperature shown on this thermometer, which is called the **wet-bulb reading.** The drier the air, the faster the evaporation and consequently the lower the wet-bulb temperature will be.

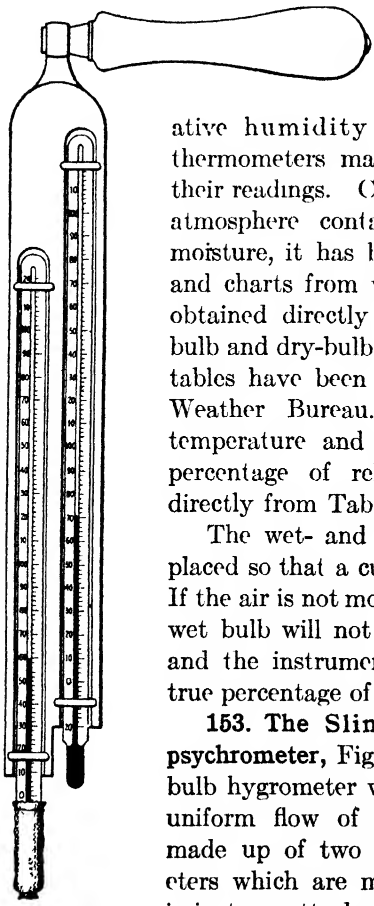


Fig. 59.—Sling psychrometer.

Experimentally it has been shown that for a given relative humidity and temperature of air, the thermometers may be depended upon to repeat their readings. Consequently, by working with an atmosphere containing a known percentage of moisture, it has been possible to establish tables and charts from which relative humidity may be obtained directly when the readings of the wet-bulb and dry-bulb thermometers are known. Such tables have been compiled by the United States Weather Bureau. By knowing the dry-bulb temperature and the wet-bulb temperature, the percentage of relative humidity may be read directly from Table XVIII.

The wet- and dry-bulb hygrometer should be placed so that a current of air will be passing by it. If the air is not moving around the hygrometer, the wet bulb will not be cooled to the proper degree, and the instrument will register higher than the true percentage of relative humidity.

153. The Sling Psychrometer.—The **sling psychrometer,** Fig. 59, consists of a wet- and dry-bulb hygrometer which can be whirled to insure a uniform flow of air by the instrument. It is made up of two accurately graduated thermometers which are mounted on a metal strip which is in turn attached to a swivel handle. The bulb of one of the thermometers is provided with a muslin cover which is soaked in water just before a humidity determination. As the psychrometer is whirled, the water surrounding the bulb of this thermometer is evaporated, thus lowering its temperature. The dry-bulb thermometer is mounted above the wet-bulb thermometer on the metal strip

Table XVIII

RELATIVE HUMIDITY

These values are correct only for an air velocity of not less than 600 ft per min and a barometric pressure of 29.92 in. Temperature readings in degrees Fahrenheit, humidity in percent.

Readings of Dry-bulb Thermometer	Difference between Readings of Wet-bulb and Dry-bulb Thermometers																				
	1°	2°	3°	4°	5°	6°	7°	8°	9°	10°	11°	12°	13°	14°	15°	16°	17°	18°	19°	20°	21°
60°	94	89	83	78	73	68	63	58	53	48	43	39	34	30	26	21	17	13	9	5	1
61°	94	89	84	78	73	68	63	58	54	49	44	40	35	31	27	22	18	14	10	7	3
62°	94	89	84	79	74	69	64	59	54	50	45	41	36	32	28	24	20	16	12	8	4
63°	95	89	84	79	74	69	64	60	55	50	46	42	37	33	29	25	21	17	13	10	6
64°	95	90	84	79	74	70	65	60	56	51	47	43	38	34	30	26	22	18	15	11	7
65°	95	90	85	80	75	70	66	61	56	52	48	44	39	35	31	27	24	20	16	12	9
66°	95	90	85	80	75	71	66	61	57	53	48	44	40	36	32	29	25	21	17	14	10
67°	95	90	85	80	75	71	66	62	58	53	49	45	41	37	33	30	26	22	19	15	12
68°	95	90	85	80	76	71	67	62	58	54	50	46	42	38	34	31	27	23	20	16	13
69°	95	90	85	81	76	72	67	63	59	55	51	47	43	39	35	32	28	24	21	18	14
70°	95	90	86	81	77	72	68	64	59	55	51	48	44	40	36	33	29	25	22	19	15
71°	95	90	86	81	77	72	68	64	60	56	52	48	45	41	37	33	30	27	23	20	17
72°	95	91	86	82	77	73	69	65	60	57	53	49	45	42	38	34	31	28	24	21	18
73°	95	91	86	82	78	73	69	65	61	57	53	50	46	42	39	35	32	29	25	22	19
74°	95	91	86	82	78	74	69	65	61	58	54	50	47	43	39	36	33	29	26	23	20
75°	96	91	86	82	78	74	70	66	62	58	54	51	47	44	40	37	34	30	27	24	21
76°	96	91	87	82	78	74	70	66	62	59	55	51	48	44	41	38	34	31	28	25	22
77°	96	91	87	83	79	74	71	67	63	59	56	52	48	45	42	39	35	32	29	26	23
78°	96	91	87	83	79	75	71	67	63	60	56	53	49	46	43	39	36	33	30	27	24
79°	96	91	87	83	79	75	71	68	64	60	57	53	50	46	43	40	37	34	31	28	25
80°	96	91	87	83	79	75	72	68	64	61	57	54	50	47	44	41	38	35	32	29	26

in order to prevent its reading from being influenced by the evaporation of this water.

During use, the instrument should be whirled at a rate of about 100 rpm. The whirling should be continued for about three-quarters of a minute, then stopped, and the thermometers quickly read. *The wet-bulb temperature should be observed first,* then the dry-bulb temperature. Immediately, two more humidity determinations should be made to serve as a check. If the air in the room is in movement, it is customary to face the breeze while making the observation, stepping from side to side while whirling the psychrometer in order to prevent bodily influence. If the determination is made out-of-doors, one should seek the shade in preference to direct sunlight. The essential precaution is to be sure that the wet bulb has been cooled to a minimum.

154. The Psychrometric Chart.—The readings obtained by the use of the sling psychrometer are usually referred to the **Psychrometric Chart,** Fig. 60, for determining the absolute humidity, the dew point, the relative humidity, and the total heat of the air. This chart, which was compiled by W. H. Carrier in 1911, is now in common use as a reference to which wet- and dry-bulb temperatures are applied for the determination of the moisture content, heat content, and density properties of the atmosphere.

Two psychrometric charts are presented in Figs. 60 and 61, covering, respectively, dry-bulb temperature ranges of 20 deg fahr to 110 deg fahr, and 80 deg fahr to 380 deg fahr.

On these charts the **dry-bulb temperatures** are represented by *vertical lines,* with the values indicated on the base line of the chart. The **wet-bulb temperatures** are represented by the *oblique lines,* with the values indicated at their intersection with the curved line A, marked "Dew-Point or Saturation Temperatures." **Dew-point temperatures** are represented by *horizontal lines* with values indicated at their intersections with the curved line A. The **percentages of relative humidity** are represented by the *converging curved lines* with values indicated thereon.

Any two of the above properties may be found if the other two are known. The following examples and the accompanying "thumb-nail" sketches of Fig. 62 are intended to illustrate the method of using the psychrometric chart.[1]

[1] These example problems and the accompanying sketches were supplied by the Carrier Engineering Corporation.

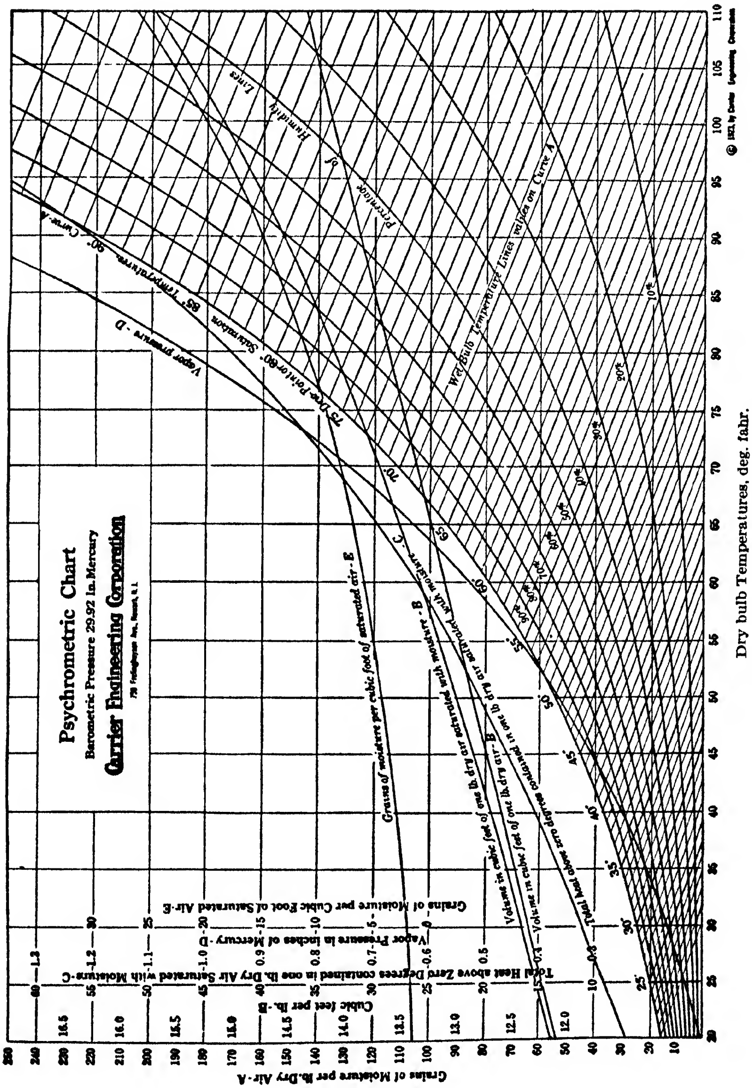


FIG. 60.—Psychrometric chart.

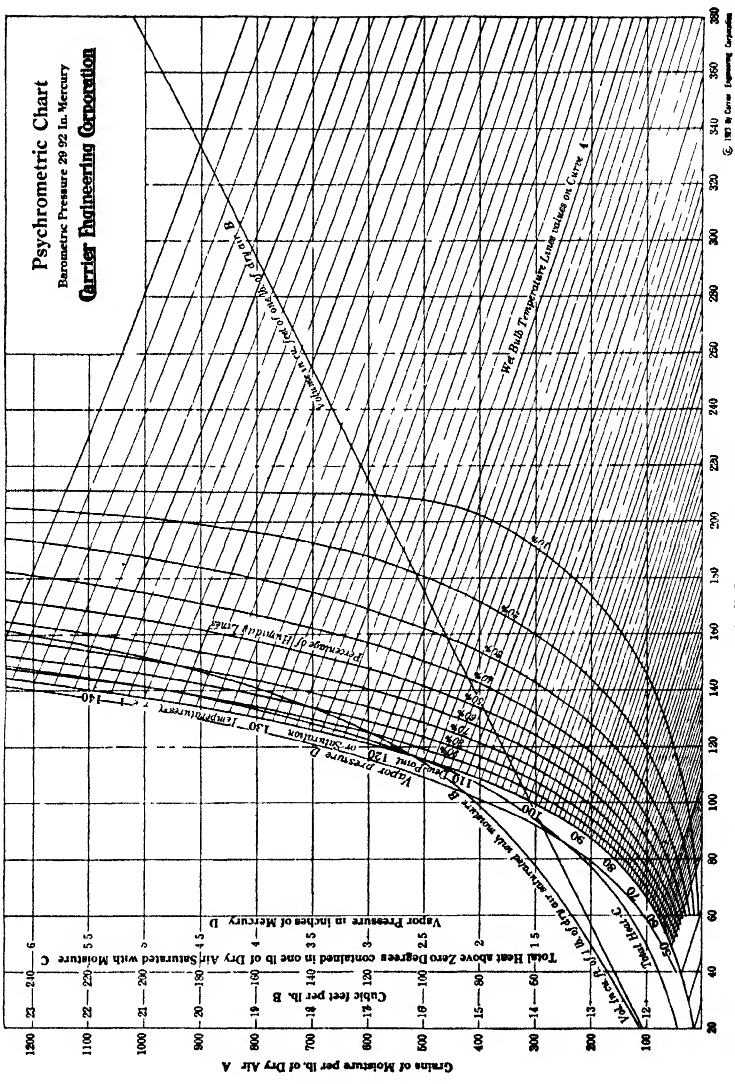


FIG. 61.—Psychrometric chart.

Example 1.

Given: Dry-bulb temperature, 70 deg fahr; wet-bulb temperature, 60 deg fahr. Find the percentage relative humidity and the dew point.

Solution.

Locate point of intersection of vertical line representing 70 deg fahr dry-bulb temperature, with the oblique line representing 60 deg fahr wet-bulb temperature. By interpolation,

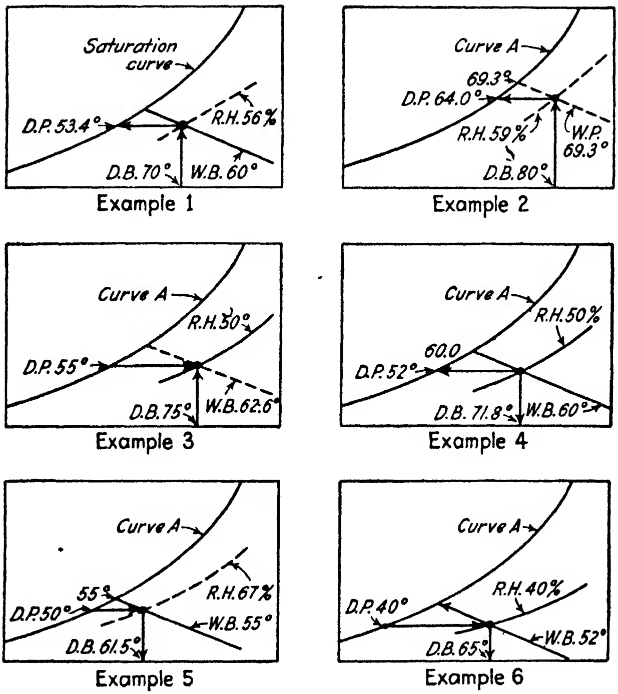


FIG. 62.—Example "thumb-nail" sketches on use of psychrometric chart.

this point indicates the percentage of relative humidity as 56 percent, and by following the intersecting horizontal line to the left to its intersection with curve A, the dew point is indicated as 53.4 deg fahr.

Example 2.

Given: Dry-bulb temperature, 80 deg fahr; relative humidity, 59 percent. Find the dew point and wet-bulb temperature.

Solution.

Locate the point of intersection of the vertical line representing 80 deg fahr dry-bulb temperature with the interpolated position of the curved line which would represent 59 percent relative humidity.

Reading horizontally to the left from this point to curve *A*, the dew point is indicated as 64 deg fahr; and reading obliquely upward to the left, between the wet-bulb lines to curve *A*, the wet-bulb temperature is indicated as 69.3 deg fahr.

Example 3.

Given: Dry-bulb temperature, 75 deg fahr; dew-point temperature, 55 deg fahr. Find percentage relative humidity and wet-bulb temperature.

Solution.

Locate the point of intersection of the vertical line representing 75 deg fahr dry-bulb temperature with the horizontal dew-point line intersecting curve *A* at 55 deg fahr.

This point indicates the relative humidity as 50 percent, and by interpolation the wet-bulb temperature as 62.6 deg. fahr.

Example 4.

Given: Relative humidity, 50 percent; wet-bulb temperature, 60 deg fahr. Find dry-bulb temperature and dew point.

Solution.

Locate the point of intersection of the curved line representing 50 percent relative humidity with the oblique line representing 60 deg fahr wet-bulb temperature.

Reading vertically downward from this point to the dry-bulb temperature on the horizontal axis of the chart, the dry-bulb temperature is indicated as 71.8 deg fahr, and reading horizontally to the left to curve *A*, the dew point is indicated as 52 deg fahr.

Example 5.

Given: Wet-bulb temperature, 55 deg fahr; dew point 50 deg fahr. Find dry-bulb temperature and relative humidity.

Solution.

Locate the point of intersection of the oblique line representing 55 deg fahr wet-bulb temperature with the horizontal line representing the dew point of 50 deg fahr.

Reading vertically downward from this point to the dry-bulb temperature axis, the dry-bulb temperature is indicated as 61.5 deg fahr; and by interpolation, the relative humidity is indicated as 67 percent.

Example 6.

Given: Relative humidity, 40 percent; dew point, 40 deg fahr. Find dry-bulb temperature and wet-bulb temperature.

Solution.

Locate the point of intersection of the curved line representing 40 percent relative humidity with the horizontal line intersecting curve A at 40 deg fahr dew-point temperature.

Reading vertically downward from this point to the dry-bulb-temperature axis, the dry-bulb temperature is indicated as 65 deg fahr; and reading obliquely upward to the left, along the wet-bulb lines to curve A, the wet-bulb temperature is indicated as 52 percent.

155. Necessity of Household Humidification.—Air at low temperatures contains only a very small quantity of water vapor; at high temperatures its capacity for holding water is increased many times. For example: at 70 deg fahr a cubic foot of saturated air contains 8 grains of moisture, whereas a cubic foot of saturated air at zero deg fahr contains approximately $\frac{1}{2}$ grain of moisture. In other words, a cubic foot of saturated air at 70 deg fahr contains sixteen times as much moisture as saturated air at zero deg fahr.

During the winter season, cold air containing a relatively small amount of moisture leaks into the house. This air is heated to room temperature, and if moisture is not added, it will be extremely dry. If, for example, the outside temperature is zero and the weather is at a normal winter humidity of 60 percent, one pound of air will contain 3.36 grains of moisture. At 70 deg fahr (room temperature) one pound of air is capable of holding 110 grains of moisture; but, unless moisture has been added as the air has been heated, the original pound of air will contain only 3.36 grains of moisture at 70 deg fahr, which means that its relative humidity would be $3.36/110 = 3.06$ percent. At such low humidities the air will absorb moisture from every available source; it will dry out the nose and throat and cause excessive evaporation from the skin, which makes one feel chilly.

It has been found that in the average residence in mid-winter, if no moisture is added to the air in any manner, the relative humidity will be between 10 and 20 percent. This is considerably drier than the Sahara desert, and should not be tolerated in a home because it is detrimental to health and comfort.

156. Quantity of Water Required for Humidification of the Average Home.—It is surprising to know just how much moisture an average home will require if the relative humidity is to be maintained at the proper percentage in cold weather. The curves in Fig. 63 show the moisture requirement for the average house for

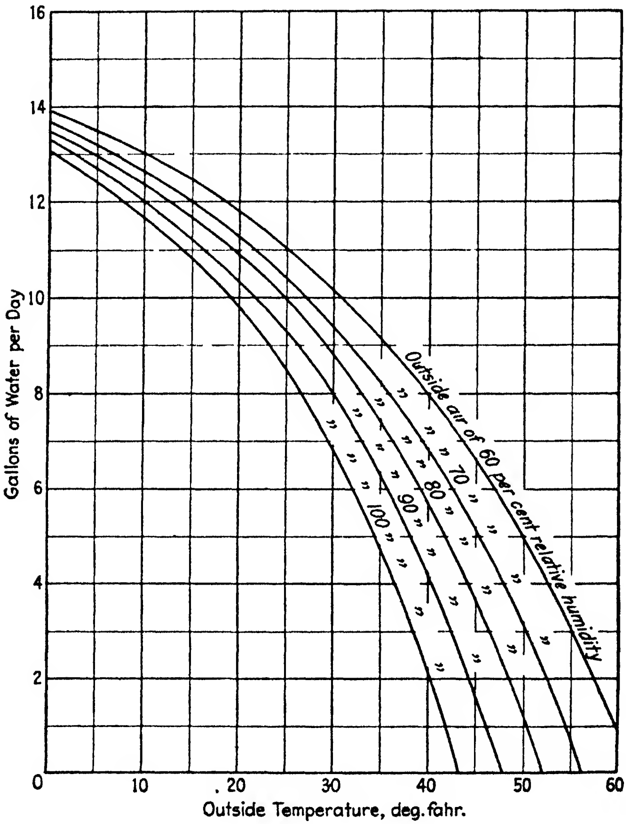


FIG. 63.—Amount of moisture required per day to humidify a 10,000 cu ft house of normal construction, assuming an inside temperature of 70 deg fahr and an inside relative humidity of 45 percent.

different outside temperatures and conditions. These curves are based on a house of good construction which has an infiltration loss of only one complete air change per hour. The house has been considered as having a total cubical content of 10,000 cu ft. The lower curve is based upon outside air at 100 percent relative

humidity, or a saturated condition, and the upper curve is for air at 60 percent relative humidity, which is the average normal outside condition in most parts of this country. The intervening curves are for conditions of 70, 80, and 90 percent relative humidity of the outside air. The purpose of the curves is to show that at low temperatures the moisture content of the outside air has very little effect on the quantity of moisture required to maintain the proper humidity in the house.

Example 1.

What quantity of moisture must be evaporated per day in a well-built house having a cubical capacity of 15,000 cu ft in order to maintain an inside humidity of 45 percent at 70 deg fahr? Assume a normal outside humidity of 60 percent accompanied by an outside temperature of 10 deg fahr.

Solution.

From the upper curve in Fig. 63 we find that 10,000 cu ft of space will require the evaporation of 13 gal of water per day for an outside temperature of 10 deg fahr. For a house of 15,000 cu ft capacity the requirement will be $(1.5 \times 13) = 19.5$ gal per day.

Example 2.

Suppose the same house as used in the foregoing example had been of such construction that the infiltration amounted to 1.5 complete air changes per hour. What would be the moisture requirement in 10-deg weather?

Solution.

The moisture requirement would be 1.5 times that required in the previous problem, or, $1.5 \times 19.5 = 29.25$ gal per day.

The curves in Fig. 63 are very general of course, because no account has been taken of the moisture that will get into the house from the occupants, from such processes as cooking and washing, etc. The moisture requirements of different types of buildings vary so much that it is impossible to state, without knowing the construction, exactly how much moisture any one house will require. A safe rule, however, is to figure that, with the average family in the average home, the heating plant must supply moisture to the amount of approximately two-thirds of the theoretical requirement as read from the curves in Fig. 63.

157. Heat Required to Evaporate Water for Humidification Purposes.—Many household humidifiers for warm-air heating

systems are of the water-pan type; that is, a pan or reservoir of water is located inside the furnace casing where it can receive heat from the furnace, and where the warm air will pass over the surface of the water. As the water is evaporated, the warm air picks up the water vapor and carries it along to the various rooms of the house. A good humidifier of this type for a 10,000 cu ft home must have sufficient capacity to hold at least 12 gal of water, and must be supplied with enough heat to evaporate this water completely in a day's time.

We know that, at 212 deg fahr and atmospheric pressure, one pound of water requires 970.2 Btu to effect a change into steam at the same temperature. The water usually enters the furnace water pan at about 60 deg fahr. So $212 - 60 = 152$ Btu are required to raise one pound of water to the boiling point before evaporation can take place. This means that the furnace must supply $970.2 + 152 = 1122.2$ Btu to evaporate each pound of water. Hence, if a house evaporates 15 gal of water per day in the humidifying process, the heat required per day to evaporate this water would be $15 \times 8.33 \times 1122.2 = 140{,}219$ Btu.

Example 1.

What quantity of heat must be supplied hourly to a water-pan type of humdifier in order to evaporate a sufficient amount of water to produce a relative humidity of 45 percent in zero weather for a house of 12,000 cu ft capacity and of normal construction? Assume a complete air change once per hour, and an outside humidity of 60 per cent.

Solution.

From the curves in Fig. 63 we see that a house of 10,000 cu ft with one air change per hour will require 14 gal of water per day, if no moisture is added by cooking, washing, etc. Taking $\frac{2}{3}$ of 14 as the average requirement under normal conditions we get 9.35 gal of water per day that must be evaporated to produce a relative humidity of 45 percent with an outside temperature of zero deg fahr. However, the house in this problem has 12,000 cu ft capacity so its moisture requirement will be $12/10 \times 9.35 = 11.2$ gal of water per day, or $11.2/24 = 0.466$ gal per hr. This equals $0.466 \times 8.33 = 3.88$ lb per hr. The heat required to evaporate this water will equal $3.88(212 - 60) + (3.88 \times 970.2) = 4354$ Btu per hr.

158. Mechanical Air Conditioning Machine.—At the present time many heating and ventilation specialists are manufacturing

air-conditioning units of specialized sizes and designs for all common types of buildings. Fig 64 is a diagrammatic sketch of a household air-conditioning unit manufactured by the Holland

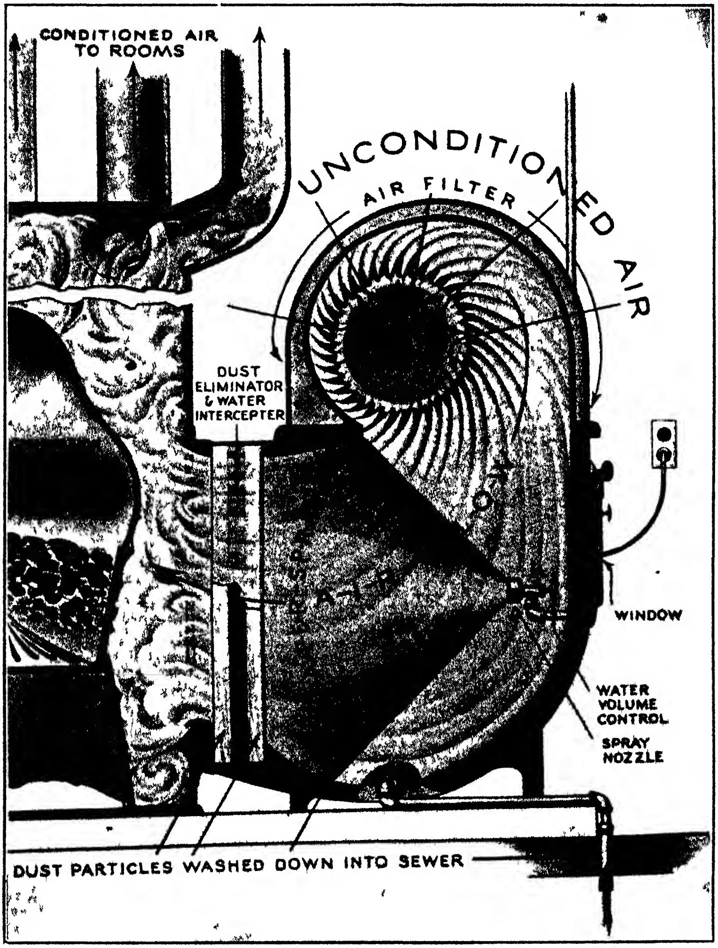


FIG. 64.—Diagram showing air-flow through a Holland air-conditioning unit.

Furnace Company, one of several concerns in the field. This equipment may be used for air humidification during the winter season and for cooling of homes during the summer months. Its operation is as follows:

Air is drawn into the conditioning unit by a high-speed motor-driven fan which is located in the top of the unit. This air is forced through a series of fine water sprays where it becomes thoroughly saturated with moisture. The moisture-laden air then passes through a dust and water eliminator and then into the heating chamber of the warm air heater where it is warmed before being distributed throughout the house. The air supplied to this unit is usually taken directly from the basement; it may, however, be taken from the outside by installing a special duct for this purpose.

If the conditioner is installed as an independent unit in homes heated with radiating systems, the conditioned air is distributed directly to the rooms from the conditioning unit by means of a special duct installation with outlets located under the radiators. The air from the rooms is returned to the basement by means of grilles suitably located in the floor. This is done to facilitate complete ventilation.

SUMMARY OF CHAPTER VIII

AIR consists of a MECHANICAL MIXTURE of several gases, the principal constituents being oxygen and nitrogen. The percentages by volume and by weight of these constituents are as follows:

	By Volume	By Weight
Oxygen	20 9	23.1
Nitrogen	79.1	76.9

The SPECIFIC HEAT of air at CONSTANT VOLUME is the quantity of heat required to raise the temperature of one pound of air one degree Fahrenheit without a change in volume.

The SPECIFIC HEAT of air at CONSTANT PRESSURE is the quantity of heat required to raise the temperature of one pound air one degree Fahrenheit without a change in pressure.

DALTON'S LAW states that the pressure produced by a mixture of several gases is equal to the sum of the individual pressures that each gas would have if the other gases were not there.

ABSOLUTE HUMIDITY defines the quantity of water mixed with the air in the atmosphere. It is usually expressed in grains per cubic foot.

RELATIVE HUMIDITY expresses the weight of moisture that air contains at a certain temperature in terms of the percentage of the amount that the air could contain if it were saturated.

The temperature at which air becomes saturated is known as the

DEW POINT. If the temperature of the air is lowered below the dew point some of the moisture will be condensed.

An apparatus commonly used in the measurement of relative humidity is the **SLING PSYCHROMETER.** It consists essentially of two mercury thermometers, the bulb of one being covered with muslin wicking which is saturated with water. These are known as dry-bulb and wet-bulb thermometers. By reading both thermometers when they have become stable, the wet-bulb depression is obtained and the relative humidity may be secured by referring these temperature readings to the Psychrometric Chart.

The relative humidity in dwelling houses should be maintained in the neighborhood of 45 per cent. In order to maintain this condition during the winter time it is necessary to supply at least 10 gal of water per day to the air in the house.

REVIEW PROBLEMS ON CHAPTER VIII

1. Define absolute humidity.

2. Define relative humidity.

3. Define dew point.

4. What is the wet-bulb temperature?

5. What is the dry-bulb temperature?

6. What instruments are used to indicate these quantities?

7. What is meant by a condition of saturation?

8. What controls the rate of evaporation of water in an open-pan humidifier?

9. What supplies the heat to evaporate the water in an open-pan humidifier?

10. Why does circulation of air increase the rate of evaporation of water from an open-pan type of humidifier?

11. What is the relative humidity and the dew point when the wet-bulb temperature is 55 deg fahr and the dry-bulb temperature 70 deg fahr?

12. What is the absolute humidity and relative humidity when the dry-bulb temperature is 40 deg fahr and the wet-bulb temperature 35 deg fahr?

13. Outside air at 20 deg fahr and 60 percent relative humidity is heated in a warm-air furnace and passed to a room at 72 deg fahr without the addition of water. What is the relative humidity of the air when it enters the room? (Hint: Secure weight of moisture per cubic foot of air either from Table XVII or from curve *E* on psychrometric chart.)

14. How much water per day must be added to the air in problem 13 to raise the relative humidity to the proper figure? Assume the room to contain 2000 cu ft and to have one complete air change per hour.

15. How can the amount of water required in problem 14 be evaporated in a house in 24 hr?

CHAPTER IX

ENERGY DIAGRAMS

159. Energy and Work.—In Chapter I, energy was defined as the ability to do work. We say that the amount of energy possessed by a body may be measured in terms of the amount of work it can do. Hence the units used to express work, namely the foot-pound, inch-pound, gram-centimeter, etc., apply directly for energy. For example, suppose a 100-lb body is suspended 15 ft above the ground. The amount of work that this body is capable of performing in returning to the ground equals 100 $\times$ 15 = 1500 ft-lb; hence, the energy possessed by the suspended body is 1500 ft-lb. In like manner, the amount of energy possessed by a compressed spring is measured in terms of the amount of work that will be accomplished when it expands. A gas compressed in a cylinder is said to possess energy since it will perform work by expanding and forcing a piston forward against an external resistance. In all these examples the amount of available energy is measured in terms of the quantity of work the body possessing the energy is capable of performing. Accordingly, we may state:

$$\left.\begin{matrix}\text{Available energy possessed}\\ \text{by a body}\end{matrix}\right\} = \left\{\begin{matrix}\text{Quantity of work the body}\\ \text{can perform}\end{matrix}\right.$$

160. Work Diagrams.—Since work is the product of two elemental terms, force and distance, it may be shown graphically as an **area** by plotting force on a vertical axis, and distance on a horizontal axis. To illustrate, suppose a constant horizontal force of 50 lb is applied to a body to move it through a horizontal distance of 10 ft. In this case, where the force is constant, the **work diagram,** Fig. 65, is a rectangle, the area of which is representative of the work done.

Work done = Force $\times$ Distance = 50 $\times$ 10 = 500 ft-lb.

Area of work diagram = Height $\times$ Base = 50 $\times$ 10 = 500 ft-lb.

Let us now consider a compressed coil spring. When the spring is allowed to expand, it is capable of moving a body against the opposing force of an external resistance. However, the force supplied by the expanding spring will vary from a maximum value when the spring is fully compressed to a value of zero when the spring is completely expanded. Let us assume that the spring exerts a force of 100 lb when fully compressed and 0 lb when expanded through 3 in. In this case the work done by the spring in expanding will be equal to the average force (50 lb) multiplied by the elongation (3 in.) Hence:

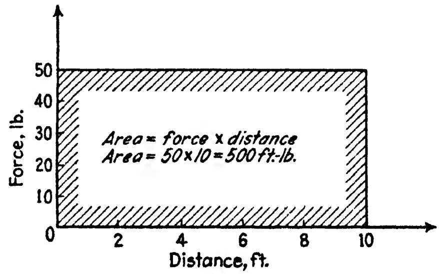


Fig. 65.—Work diagram.

$$\text{Work done} = \text{Average force} \times \text{Elongation.}$$

$$\text{Work done} = \frac{100}{2} \times 3 = 150 \text{ in-lb.}$$

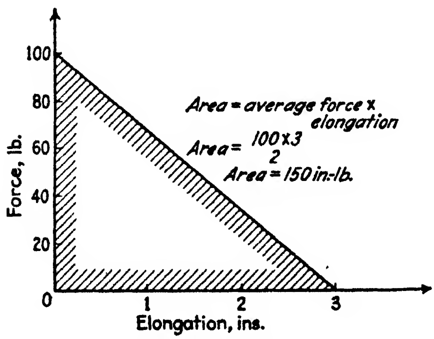


Fig. 66.—Work diagram showing work done by a coil spring in expanding.

Since the force acting is constantly decreasing, the work diagram, Fig. 66, is a triangle, the area of which is equal to the work done.

Area of work diagram

$$= \frac{\text{Altitude} \times \text{Base}}{2}$$

$$= \frac{100 \times 3}{2} = 150 \text{ in-lb.}$$

161. Pressure-volume Diagrams (General Case).—In Fig. 67, pressure in pounds per square foot absolute are shown on the vertical scale, and volume in cubic feet on the horizontal scale. If the compressed gas to the left of the piston at L_1 is allowed to expand to the second location at L_2, the gas pressure will decrease as the volume occupied by the gas increases. This is shown by

the curve 1–2. The area under the curve 1–2 is equal to the average pressure acting during expansion multiplied by the cor-

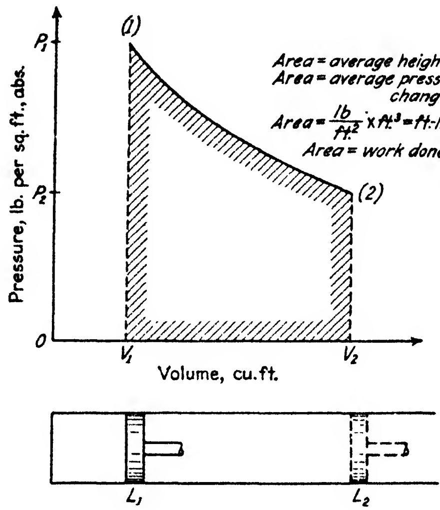


FIG. 67.—Diagram showing the work done by a gas in expanding (general case).

responding change in volume or pounds/square feet × cubic feet = foot-pounds, that is, work. Hence the area under the curve represents the amount of work done by the gas in forcing the piston from L_1 to L_2.

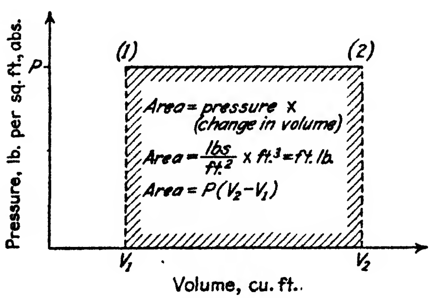


FIG. 68.—Work diagram for constant-pressure expansion.

162. Constant Pressure Expansion (Isobaric).—The area of Fig. 68 represents the work done by a gas in moving a piston from position V_1 to position V_2 at constant pressure. This area is equal to the product of the pressure acting and the change in cylinder volume, or:

$$W = P(V_2 - V_1) \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

in which

W = work performed by expansion of gas, ft-lb.
P = pressure of gas, lb per sq ft.
V_1 = original volume of gas, cu ft.
V_2 = final volume of gas, cu ft.

Example 1.

In Fig. 68, $V_1 = 15$ cu ft. and $V_2 = 100$ cu ft. Determine the quantity of work done if the pressure acting during expansion is 120 lb per sq in.

Solution.

$$W = P(V_2 - V_1)$$
$$W = 144 \times 120(100 - 15)$$
$$W = 1{,}468{,}800 \text{ ft-lb.}$$

163. Constant Temperature Expansion (Isothermal).—The curve 1–2 in Fig. 69 represents the path of change when a gas is expanded from volume V_1 to volume V_2 at constant temperature. An expansion of this kind, where the gas temperature remains constant throughout the change, is referred to as an **isothermal** expansion, and it obeys the law $P_1V_1 = P_2V_2$.

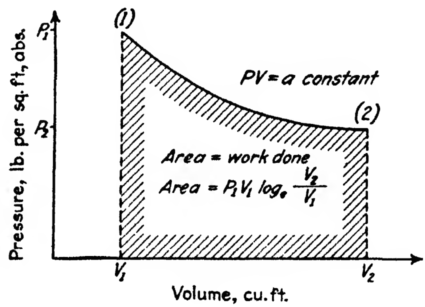


FIG. 69.—Work diagram for constant-temperature expansion.

The shaded area under the curve 1–2 represents the quantity of work done by the gas in expanding from volume 1 to volume 2. This area, or the work done during expansion, is expressed by the following formula:

$$\text{Area} = W = P_1V_1 \log_e\left(\frac{V_2}{V_1}\right) \quad . \quad . \quad . \quad . \quad (46)^*$$

in which

W = work done by gas, ft-lb.
P_1 = original pressure of gas, lb per sq ft. abs.
V_1 = original volume of gas, cu ft.
V_2 = final volume of gas, cu ft.
$\log_e = 2.3 \log_{10}$.

* See footnote p. 195.

The quantity of work, W, may be easily converted into heat units by dividing the foot-pounds by 778, thus obtaining the equivalent quantity of heat in Btu.

Example 1.

A given quantity of gas is expanded in a cylinder in such a manner that its temperature remains constant during the expansion. The original pressure of the gas is 150 lb per sq in. abs, and it occupies a volume of 10 cu ft. If the final gas pressure is 25 lb per sq in. abs, how much work is done by the gas in expanding?

Solution.

$$P_1V_1 = P_2V_2$$

$$150 \times 10 = 25 \times V_2$$

$$V_2 = \frac{150 \times 10}{25} = 60 \text{ cu ft.}$$

$$\text{Work done} = P_1V_1 \log_e \frac{V_2}{V_1}$$

$$\text{Work done} = 144 \times 150 \times 10 \log_e \tfrac{60}{10}$$

$$\text{Work done} = 216{,}000 \log_e 6$$

But $\log_e 6 = 2.3 \log_{10} 6 = 2.3 \times 0.7782 = 1.79$

Thus Work done $= 216{,}000 \times 1.79 = 386{,}730$ ft-lb.

164. Constant Entropy Expansion (Adiabatic).—Suppose we have an air-compressor cylinder filled with air, and suppose that the construction of the cylinder is such that there is neither leakage of air by the piston nor friction, and that the wall of the cylinder, as well as the piston, are constructed of non-heat-conducting material. If the piston compresses the air quickly, no energy will be lost from the air by conduction or radiation, that is, as heat. Hence, the external work done in compressing the gas will appear in the gas as potential energy due to its pressure, and as kinetic energy due to its heat content. A compression of this nature is called an adiabatic compression, and would be in accordance with the formula:

$$PV^n = \text{a constant}$$

or

$$P_1V_1^n = P_2V_2^n \qquad (47)^*$$

* See footnote p. 195.

The exponent n in the foregoing equation represents the ratio of S_p to S_v, or:

$$n = \frac{S_p}{S_v}$$

Thus n for air is:

$$\frac{0.2375}{0.1689} = 1.41$$

(Obtain values of S_p and S_v from Table III on page 62.)

An adiabatic expansion or compression assumes that no heat is lost or gained **as heat,** that is, by conduction, convection, or radiation. In this event, any energy lost by the gas must be lost through the performance of external work.

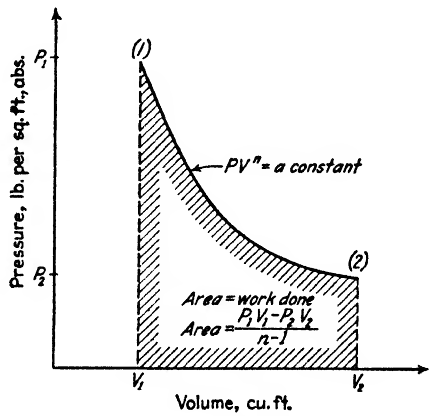


FIG. 70.—Work diagram for constant-entropy expansion.

Fig. 70 shows the path of the change which takes place when a gas expands from condition 1 to condition 2 adiabatically. The shaded area under this curve represents the external work done by the gas.

The external work, W, done during the adiabatic expansion of a perfect gas may be expressed by the following formulas:

$$W = \frac{P_1V_1 - P_2V_2}{n - 1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (48)^*$$

or

$$W = \frac{wR(T_2 - T_1)}{n - 1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (49)^*$$

* The formal derivation of equations 46, 47, 48 and 49 take more space and more of a mathematical treatment than the scope of this text permits. The student desiring to inspect these derivations is referred to Chapter II of "Steam, Air and Gas Power," by Severns and Degler, published by John Wiley and Sons, Inc., New York City.

in which

V_1 = initial volume of gas, cu ft.
V_2 = final volume of gas, cu ft.
W = work done, ft-lb.
P_1 = initial pressure of gas, lb per sq ft. abs.
P_2 = final pressure of gas, lb per sq ft. abs.
T_1 = initial absolute temperature of gas, deg fahr.
T_2 = final absolute temperature of gas, deg fahr.
R = constant depending on nature of gas. (See Table III.)

$$n = \frac{S_p}{S_v} = \frac{\text{specific heat at constant pressure}}{\text{specific heat at constant volume}}. \quad \text{(See Table III.)}$$

Example 1.

Suppose that an air compressor receiving air from a room at 70 deg fahr was to compress 20 cu ft. of this air adiabatically to an absolute pressure of 120 lb per sq in. What would be the temperature of the air as it left the compressor?

Solution.

First, find the volume occupied by the air at 120 lb per sq in. abs. Let us assume the original pressure of the air taken from the room to be 14.7 lb per sq in. abs.

$$P_1V_1^n = P_2V_2^n$$
$$14.7 \times 20^{1.41} = 120 \times V_2^{1.41}$$
$$V_2^{1.41} = \frac{14.7 \times 20^{1.41}}{120}$$
$$1.41 \log V_2 = (\log 14.7) + (1.41 \log 20) - (\log 120)$$
$$1.41 \log V_2 = (1.1673) + (1.41 \times 1.3010) - (2.0792)$$
$$1.41 \log V_2 = 1.1673 + 1.8344 - 2.0792$$
$$1.41 \log V_2 = 0.9225$$
$$\log V_2 = \frac{0.9225}{1.41} = 0.655$$
$$V_2 = 4.52 \text{ cu ft.}$$

The new volume of the air after adiabatic compression would therefore be 4.52 cu ft. Now, using the general gas law equation, we can solve for the final temperature.

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$
$$\frac{14.7 \times 20}{(70 + 460)} = \frac{120 \times 4.52}{T_2}$$

$$T_2 = \frac{120 \times 4.52 \times 530}{14.7 \times 20} = 980 \text{ deg fahr abs}$$

$$t_2 = 980 - 460 = 520 \text{ deg fahr.}$$

Example 2.

Determine the quantity of work done by the compressor in the foregoing problem.

Solution.

$$\text{Work done by gas} = \frac{P_1V_1 - P_2V_2}{n - 1}$$

$$\text{Work done by gas} = \frac{(144 \times 14.7 \times 20) - (144 \times 120 \times 4.5)}{1.41 - 1}$$

$$\text{Work done by gas} = \frac{42{,}336 - 78{,}105}{0.41} = -\ 87{,}200 \text{ ft-lb.}$$

The minus sign (−87,200 ft-lb) indicates that the gas did not deliver work but rather received 87,200 ft-lb of work from the compressor. This will be understood when it is realized that the equation $\frac{P_1V_1 - P_2V_2}{n - 1}$ applies to adiabatic expansion rather than to adiabatic compression.

165. Work Diagram for Steam Engine Cylinder.—Fig. 71 shows a "work diagram" representing the conditions in a steam-engine cylinder during operation of the engine. The vertical height of the diagram at any point represents the unit steam pressure in pounds per square inch acting against the piston; and the horizontal distance, the corresponding position of the piston. Steam enters the cylinder at point A, and the pressure acting on the piston rises until point B is reached. As the piston moves forward from B to C, steam is constantly supplied to the cylinder, and as a result the drop in pressure during this portion of the piston stroke is small.

At C the steam inlet valve is closed, and the steam contained in the cylinder expands, driving the piston almost to the end of its stroke at D, where the exhaust valve opens. As soon as the exhaust valve is opened the pressure within the cylinder drops to that at E. On the return stroke of the piston the pressure remains practically constant from E to F; at F the exhaust valve is closed and the steam remaining in the cylinder is compressed from F to A. At A, steam is again admitted to the cylinder, and the foregoing cycle of events is repeated.

The area of this work diagram equals the product of the

average height of the diagram and its length. The average height of an irregular figure such as this can be found approximately by measuring the height at 15 to 20 points located at equal intervals along the entire length of the diagram; the numerical average of these measured heights will approximately equal the average height of the figure. A more accurate determination of the area of the work diagram may be found by measuring the area directly with a planimeter, an instrument designed for the measurement of irregular areas.

Since the vertical axis in this diagram represents the force acting on only one square inch of the engine piston, the area of the

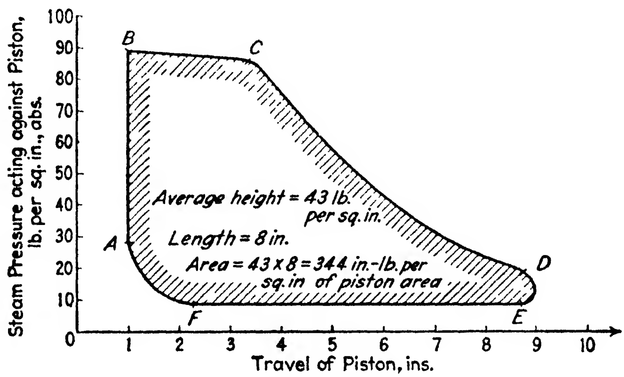


FIG. 71.—Steam engine cylinder work diagram.

diagram indicates the work done per square inch of piston area. If it is desired to find the total quantity of work accomplished by the action of the steam against the engine piston, the work per square inch of the piston area obtained from the work diagram must be multiplied by the area of the piston. Thus, in Fig. 71, if the average height of the diagram indicates 43 lb per sq in. and the length 8 in., the quantity of work $= 43 \times 8 = 344$ in-lb per sq in. of piston area. If this diagram were obtained from an engine having a piston of 40 sq in. area, the total quantity of work accomplished by the engine piston, on one side of the piston per revolution of the crank, would equal $344 \times 40 = 13{,}760$ in-lb, or $13{,}760/12 = 1146.6$ ft-lb.

166. Entropy.—The foregoing material in this chapter points out that energy is the product of two elemental factors—one an *intensity* factor, and the other a *distribution* factor. For mechani-

cal energy the intensity factor is *force*, and the distribution factor is the *distance* through which the force is exerted. For the energy released by a gas in expanding, the intensity factor is the average *pressure* acting during the expansion, and the distribution factor is the change in *volume* of the gas. In each of these kinds of energy, both the intensity and the distribution factors are of such a nature as to be readily measurable.

Let us now turn our attention to heat energy. The *intensity factor in this case is temperature*, which is obtainable by direct measurement with a thermometer. Temperature alone, however, is no more a measure of heat energy than force alone is a measure of mechanical energy—a distribution factor is now necessary. This distribution factor must bear the same relation to heat energy as distance does to mechanical energy. The name **entropy** has been given to the *distribution factor* that fulfills these requirements. Entropy, however, is a factor which cannot be measured by means of an instrument, and is unfortunately imperceptible to the human senses.

Thus we may say that the heat content of a body can be expressed as a function of its absolute temperature and its entropy. For the latent heat state, the entropy N can be found by dividing the latent heat content of the body by its absolute temperature. This relationship may be expressed as follows:

$$N = \frac{L}{T}. \qquad \qquad (50)$$

Fig. 72 represents a *temperature-entropy diagram* in which absolute temperature is plotted on the vertical axis and entropy on the horizontal axis. A given volume of gas is cooled from temperature T_1 to temperature T_2, the change taking place along the line 1–2. The area under the curve 1–2 represents the change in heat energy, and $\phi_2 - \phi_1$ the corresponding change in entropy.

167. Entropy of Steam.—The entropy of steam, ϕ, as given in the last column of the steam tables (Table V), is equal to the entropy of the water, θ, plus the entropy of evaporation, L/T. Thus $\phi = \theta + L/T$. If the steam is superheated there is a corresponding value for the entropy of superheat, n. Thus the total entropy for superheated steam equals $\theta + L/T + n$.

The entropy of evaporation, L/T, is found by dividing the latent heat of the steam by the corresponding absolute tempera-

ture in degrees Fahrenheit. Thus the change in entropy during the evaporation of one pound of water at atmospheric pressure $= 970.2/(212 + 460) = 1.4446$ Btu per deg fahr abs.

Throughout technical literature the entropy of the liquid, θ, is arbitrarily said to be zero when the temperature of the water is 32 deg fahr. Thus, if the temperature of the water was 33 deg fahr, the entropy of the water at this temperature would be 1/493, since 1 Btu would represent the quantity of heat required

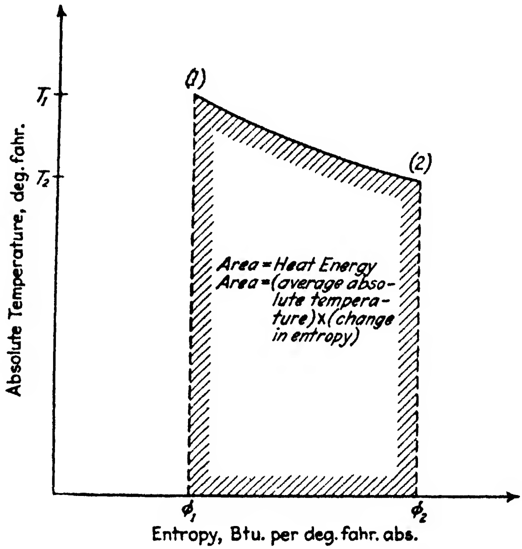


FIG. 72.—Temperature-entropy diagram.

to heat the water from 32 to 33 deg fahr, and 493 the absolute temperature of the water.

The entropy of the liquid at 212 deg fahr would be the sum of the series:

$$\theta_{212} = \frac{1}{493} + \frac{1}{494} + \frac{1}{495} + \text{etc., to } \frac{1}{672} = 0.3119$$

The entropy of dry and saturated steam at 212 deg fahr would be:

$$\phi = \theta + \frac{L}{T}$$

$$\phi = 0.3119 + \frac{970.2}{672} = 1.7564$$

On the other hand, if the steam contains moisture and has a quality of 99 per cent, the entropy of the steam would be:

$$\phi = \theta + \frac{xL}{T}$$

$$\phi = 0.3119 + \frac{0.99 \times 970.2}{672} = 1.7500$$

If we have steam under a pressure of 14.7 lb per sq in. abs and its entropy is 1.8000 instead of 1.7564, we know that it contains more energy than dry and saturated steam, i.e., it is superheated enough to give it an additional entropy of 1.8000 − 1.7564 = 0.0436 above that of dry and saturated steam. If the specific heat of the steam is assumed to remain constant at 0.48, then the entropy of superheat, n, equals:

$$n = 0.0436 = \frac{0.48}{673} + \frac{0.48}{674} + \frac{0.48}{675} + \text{etc., to } \frac{0.48}{(672 + d)}$$

where d = the number of degrees of superheat.

The total entropy of this superheated steam would be made up of the following:

$$\phi = \theta + \frac{L}{T} + n$$

$$\phi = 0.3119 + \frac{970.2}{672} + 0.0436 = 1.8000$$

168. Entropy Diagrams for Steam.—Changes which take place during the formation and usage of steam may be represented graphically by means of:

1. Pressure-volume diagrams.
2. Temperature-total heat diagrams.
3. Temperature-entropy diagrams.
4. Total heat-entropy diagrams.

Thus far we have studied only the significance of 1 and 2 We now turn our attention to an understanding of 3 and 4.

169. Temperature-entropy Diagram for Steam.—Fig. 73 represents a temperature-entropy diagram for the formation of superheated steam from one pound of water at 32 deg fahr. It is con-

structed with absolute temperature plotted on the vertical axis and entropy on the horizontal axis. The line *abcd* represents the path of the change which takes place when one pound of water is heated from 32 deg fahr. The **liquid line,** *ab,* shows the change in entropy ($\phi_1 - 0$) with respect to the change in absolute temperature ($T_v - 492$). The area under the liquid line represents the

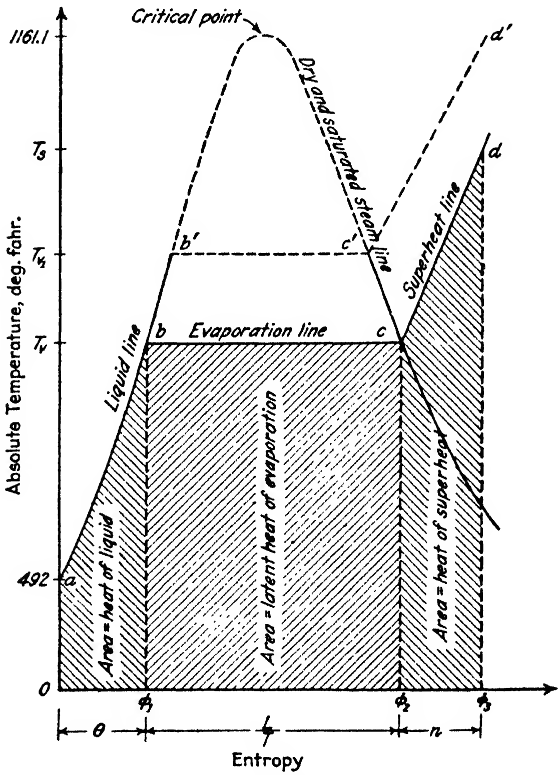


FIG. 73.—Temperature-entropy diagram for the formation of steam.

quantity of heat supplied to raise the temperature of the one pound of water from 32 deg fahr to T_v, that is, the heat of the liquid. The line *bc* is known as the **evaporation line** and shows the increase in entropy ($\phi_2 - \phi_1$) which takes place during the evaporation of the steam. The area under the evaporation line is equal to the quantity of heat delivered to the steam during its evaporation. Thus point *c* defines the temperature and entropy of one pound of

water that has been completely evaporated into steam. If additional heat be supplied to the steam after this point is reached, the steam becomes superheated and the path of the change follows the **superheat line** *cd*. In a similar manner the area under the line *cd* represents the quantity of heat supplied to the pound of steam in order to heat it from T_v to T_s, and $(\phi_3 - \phi_2)$ represents the corresponding change in entropy that takes place.

The curve *ab'c'd'* represents the path of change that takes place when the steam is formed at a higher pressure. In this case heat is supplied to the liquid until it reaches the temperature T_{v1}, the boiling-point temperature corresponding to this pressure.

It will be observed that the liquid line and the dry and saturated steam line intersect at a temperature of 1166.1 deg fahr abs, or 1166.1 − 460 = 706.1 deg fahr. This temperature is referred to as the **critical temperature** for steam since it represents a condition under which water is converted directly into steam without the addition of latent heat.

170. Total Heat-entropy Diagram for Steam (Mollier Diagram).—Fig. 74 shows a total heat-entropy chart prepared with

Fig. 74.—Mollier diagram.

This illustration is a folding chart placed at the back of the book.

total heat above 32 deg fahr for one pound of steam as vertical distances and entropy as horizontal distances. This chart affords an easy means of solution of many problems which would otherwise require long and complicated numerical solutions. In using it, the following points should be clearly understood:

1. Horizontal lines represent lines of constant total heat.
2. Vertical lines represent lines of constant entropy.
3. Lines sloping upward to the right represent lines of constant absolute pressure.
4. The heavy black line sloping downward to the right at the middle of the chart is the dry and saturated steam line. The region above this line is the superheated steam region, and the region below this line is the wet steam region.
5. Lines sloping downward to the right below the dry and saturated steam line are lines of constant quality.
6. Lines sloping downward to the right above the dry and saturated steam line are lines of constant superheat.

An understanding of the method of using this chart will be best obtained from studying the solution of the following problems.

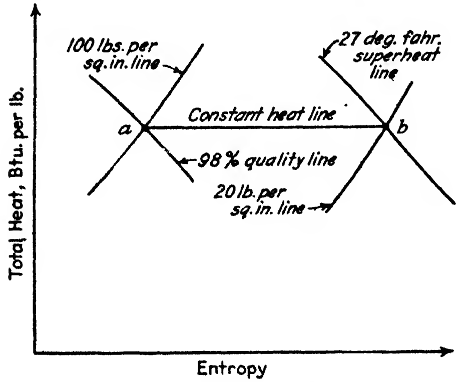


FIG. 75.—Portion of total heat-entropy diagram of Fig. 74 which pertains to Example 1, Art. 170.

Example 1.

One pound of steam at 100 lb per sq in. abs pressure and 98 percent quality is expanded without change in total heat to a pressure of 20 lb per sq in. Determine number of degrees of superheat at the lower pressure.

Solution.

Fig. 75 represents a portion of the total heat-entropy diagram of Fig. 74. Point *a* represents the intersection of the 100 lb per sq in. abs pressure line with the 98 percent quality line. From point *a* follow the horizontal constant heat line until it intersects the 20 lb per sq in. abs pressure line at *b*. The superheat corresponding is found to be 27 deg.

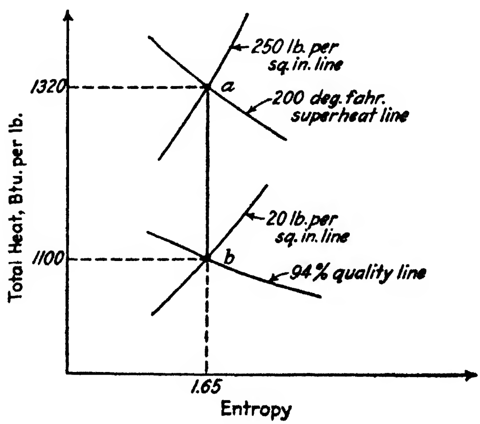


FIG. 76.—Portion of total heat-entropy diagram of Fig. 74 which pertains to Example 2, Art. 170.

Example 2.

One pound of steam is expanded in an engine cylinder in such a manner that its entropy remains constant during the expansion. If the original steam is at 250 lb per sq in. abs and has 200 deg of superheat, what is the quality of the steam at exhaust if the pressure at exhaust

is 20 lb per sq in. abs? How many Btu were given up by the steam during expansion?

Solution.

Fig. 76 represents the portion of the total heat-entropy diagram which relates to this problem. Locate the intersection of the 250 lb per sq in. pressure line with the 200 deg fahr superheat line. This is point *a*. From point *a*, follow the vertical constant entropy line until it intersects the 20 lb per sq in. pressure line at *b*. The quality corresponding is found to be 94 percent.

The quantity of heat given up by the pound of steam is equal to the difference between the total heat content at *a* and *b*, or 1320 − 1100 = 220 Btu.

SUMMARY OF CHAPTER IX

The AVAILABLE ENERGY possessed by a body may be measured in terms of the quantity of WORK the body is capable of performing.

WORK, being the product of force and distance, may be expressed graphically by means of a WORK DIAGRAM. The AREA of a work diagram is equal to the quantity of WORK DONE.

A PRESSURE-VOLUME DIAGRAM represents the change in pressure which takes place in a cylinder with respect to a change in volume. The AREA under a pressure-volume curve represents the WORK DONE BY the gas during expansion, or the WORK DONE ON the gas during compression.

The work done by the gas during a CONSTANT PRESSURE expansion is expressed by the formula:

$$W = P(V_2 - V_1)$$

The work done by the gas during an ISOTHERMAL expansion is expressed by the formula:

$$W = P_1V_1 \log_e \frac{V_2}{V_1}$$

An ADIABATIC EXPANSION of a gas is one in which no energy is LOST OR GAINED as heat, any change in energy being in the form of WORK.

The work done by a gas during an ADIABATIC expansion is expressed by the formula:

$$W = \frac{P_1V_1 - P_2V_2}{n - 1}$$

ENTROPY is the distribution factor of heat. The ENTROPY of steam is equal to the ENTROPY of the water plus the ENTROPY of evaporation, i.e., $\phi = \theta + \frac{L}{T}$.

The TEMPERATURE-ENTROPY DIAGRAM for steam is useful in giving a more complete understanding of the physical changes which take place during the formation and usage of steam.

The TOTAL HEAT-ENTROPY DIAGRAM for steam offers an easy solution for many problems which would otherwise involve long and tedious calculations.

REVIEW PROBLEMS ON CHAPTER IX

1. A weight of 100 lb is lifted vertically through a distance of 15 ft. Plot the work diagram representing the work done.

2. A force of 180 lb is required to compress a coil spring through a distance of 6 in. If the force required to compress the spring varies directly with its deformation, how much work is done in compressing the spring through 5 in.? Show graphically.

3. Two cubic feet of air at 100 lb per sq in. abs is expanded without change in pressure to a volume of 4.5 cu ft. Determine the quantity of work done in foot-pounds. What quantity of heat does this represent?

4. A given weight of air is expanded isothermally (at constant temperature) from an initial pressure of 100 lb per sq in. abs to a final pressure of 14.7 lb per sq in. abs. If the initial volume of the air was 3.5 cu ft, find the following:

(*a*) Final volume of the air.
(*b*) Quantity of work done during expansion.
(*c*) Heat equivalent of the work done.

5. Fifteen cubic feet of air is expanded adiabatically from a pressure of 85 lb per sq in. abs and a temperature of 350 deg fahr to a pressure of 25 lb per sq in. abs. Find:

(*a*) The volume of the air at the end of expansion.
(*b*) The work done during expansion.
(*c*) What quantity of heat did the air absorb?

6. Determine the quantity of work delivered by 10 cu ft of air at 75 lb per sq in. abs and 180 deg fahr in expanding adiabatically to normal atmospheric pressure.

7. Determine the change in entropy when one pound of a substance having a specific heat of 0.20 is heated from 70 to 240 deg fahr.

8. Obtain, by the use of the total heat-entropy diagram (Fig. 74), the quality of steam after expanding from a pressure of 120 lb per sq in. abs as dry steam to a pressure of 35 lb per sq in. abs. Assume constant entropy throughout the change.

9. One pound of dry steam is expanded at a constant pressure of 200 lb per sq in. abs to a condition of 90 percent quality. Find:

(*a*) Quantity of heat given up by the steam.
(*b*) What quantity of work does (*a*) represent?
(*c*) What change in entropy occurs during this expansion?

10. Ten pounds of steam is expanded at constant entropy from a pressure of 150 lb per sq in. abs and 200 deg of superheat to a pressure of 40 lb per sq in. abs. Determine the quality of the steam at the end of the expansion and the total quantity of heat theoretically converted into work. How many foot-pounds of work are delivered?

APPENDIX A

THERMOMETRY PROBLEMS

4a. How many Centigrade degrees are there between the freezing and boiling points? How many Fahrenheit degrees?

4b. Which represents the greater change in temperature, 1 deg fahr or 1 deg cent? In what ratio?

5a. Give the corresponding Centigrade change in temperature for each of the following changes in Fahrenheit: 1 deg, 9 deg, 18 deg, 27 deg, 36 deg, 45 deg, 52 deg, 2 deg, 5 deg, 11 deg, 13 deg, 17 deg.

5b. Give the corresponding Fahrenheit change in temperature for each of the following changes in Centigrade: 1 deg, 5 deg, 10 deg, 15 deg, 20 deg, 25 deg, 30 deg, 35 deg, 2 deg, 3 deg, 4 deg, 6 deg, 11 deg, 13 deg.

5c. How many Centigrade degrees above freezing is 60 deg cent? How many Fahrenheit degrees above freezing is 60 deg cent; 60 deg cent is what temperature in degrees Fahrenheit? How many Fahrenheit degrees above freezing is 41 deg fahr; how many Centigrade degrees above freezing is 41 deg fahr; 41 deg fahr is what temperature in degrees Centigrade?

5d. Convert the following Fahrenheit temperatures into Centigrade temperatures: 50 deg, 59 deg, 68 deg, 77 deg, 21 deg, 12 deg, 2 deg, − 7 deg, − 16 deg, − 20 deg, − 25 deg, 81 deg, 3 deg, 242 deg, 300 deg.

5e. Convert the following Centigrade temperatures to Fahrenheit temperatures: 5 deg, 10 deg, 15 deg, 20 deg, − 5 deg, − 10 deg, − 55 deg, 62 deg, 211 deg, − 36 deg.

5f. A correct Centigrade thermometer read 20 deg cent for the temperature of a solution into which the thermometer was immersed. A Fahrenheit thermometer read 70 deg fahr in the same solution. How many degrees in error was the Fahrenheit thermometer? Would this error have to be added or subtracted from the thermometer reading to obtain the true temperature?

5g. A thermometer read 211 deg fahr in steam and 30 deg fahr in melting ice. What would it read when the true temperature to which it was exposed was 65 deg fahr? Assume uniform marking and uniform bore.

5h. A thermometer was designed with 80 deg between the fixed points, and the freezing point was taken as 0 deg. What would be the

reading on this thermometer when the temperature to which it was exposed was 105 deg fahr?

HEAT ENERGY PROBLEMS

12a. Express the following energy changes in both Btu and Calories:

1 lb water raised 1 deg cent.
1 ton water raised 1 deg cent.
1 ton water raised 1 deg fahr.
1 kg water raised 1 deg fahr.
5 kg water raised 3 deg fahr.
7 lb water raised 6 deg cent.
8 lb water raised 15 deg fahr.
53 lb water raised 28 deg cent.

13a. How many heat units are required to raise the temperature of 300 lb of lead from 32 deg fahr to 56 deg fahr, assuming the specific heat of lead to be 0.0315?

13b. How many Btu would be required to raise 4 lb of aluminum from 0 deg fahr to 328 deg fahr? (Specific heat of aluminum = 0.212.)

13c. How many Btu are necessary to raise the temperature of 1 ton of water from 40 deg fahr to 182 deg fahr?

13d. A cast-iron bearing weighs 20 kg. How many calories will heat it from 12 deg cent to 200 deg cent? (Specific heat of iron = 0.12.)

13e. How many Btu will raise 20 lb of air from 10 deg cent to 25 deg cent under conditions of standard pressure? The specific heat for air at standard pressure is 0.236.

13f. How many Btu are required to heat 12 lb of air from 60 deg fahr to the temperature of a furnace fuel bed known to be at 2300 deg fahr? Assume the specific heat of air to average 0.240 for this range of temperature.

13g. How much energy in Btu would be required to heat 1 lb of coal from 60 deg fahr to 2300 deg fahr, if the specific heat of coal over this range equals 0.22?

13h. How many Btu per hour will it be necessary to extract from the air to cool an auditorium 132 ft by 70 ft by 28 ft, when the air is supplied at 43 deg fahr and withdrawn at 85 deg fahr? Assume the air to have a weight of 0.0685 lb per cu ft and a specific heat of 0.236, the auditorium having 5 air changes per hour.

13i. If 4820 Btu were supplied to 250 lb of copper having a specific heat of 0.094, what would be the resulting temperature change?

13j. If, in problem **13i,** zinc had been used instead of copper, what would have been the temperature change. (Specific heat of zinc = 0.095.)

13k. If 27,600 Btu are required to raise 500 lb of oil from 100 deg fahr to 209 deg fahr, what is the specific heat of the oil?

13l. If the heat lost by the cooling of 18.7 lb of water from 155 deg fahr to 43 deg fahr is used to heat 350 lb of lead whose specific heat = 0.032, through what temperature range would the lead be heated?

13m. Ten pounds of cast iron at 212 deg fahr is cooled to 80 deg fahr by plunging it into 5 lb of water. How many Btu are given up by the iron? If all this heat is absorbed by the water, what must its temperature have been before the iron was plunged into it, assuming that the entire weight of water reached the temperature of 80 deg fahr as a final condition?

PROBLEMS ON WORK AND POWER

15a. A weight of 2000 lb is hoisted vertically upward by a derrick. How many foot-pounds of work are done if the weight is lifted 5 ft? 10 ft? 15 ft? 25 ft?

15b. An automobile is towed for a distance of 225 ft by a pull of 50 lb. How much work is done?

15c. If 50 gal of water are pumped from the basement of a house to the top floor, a distance of 26 ft, what is the amount of work so expended? (One gal = $8\frac{1}{3}$ lb.)

15d. How much work is done by a man weighing 140 lb in going up a flight of stairs 14 ft high?

15e. If it takes 10 sec for the automobile in problem **15b** to travel the 225 ft, how many foot-pounds of work were accomplished each second?

16a. What power would be required to pump 10 cu ft of water to a height of 200 ft in 100 sec? An engine of what horsepower would be required to accomplish this result?

17a. An elevator weighing 1500 lb ascends at the rate of 1 ft per sec. What horsepower is being exerted by the hoisting motor?

17b. A steam hoisting engine raises a block of marble weighing 300 lb through a vertical distance of 180 ft in 5 sec. What is the horsepower of the engine?

17c. What weight could a 20-hp engine raise 100 ft in 2 sec?

17d. An automobile delivers 45 hp to the wheels when traveling at a rate of 60 mph. What is the total resistance to motion?

17e. A water turbine having an efficiency of 70 percent develops 500 hp under a head of 45 ft. What is the rate of flow of water in cubic feet per minute?

17f. A certain hydroelectric plant has turbines of 75 percent efficiency and generators of 92 percent efficiency. The plant is supplied with water at the rate of 72,000 cu ft per min under a 100-ft head. What is the horsepower output of the generators? (One cubic foot of water weighs 62.5 lb.)

18a. How many horsepower-hours are delivered by an engine that is supplying 35 hp for a period of 6 hr? If the total operating cost for the 6-hr period is $4.20, what is the operating cost per horsepower-hour?

18b. One horsepower-hour is equal to how many foot-pounds?

PROBLEMS INVOLVING MECHANICAL AND ELECTRICAL EQUIVALENTS OF HEAT

20a. The following data were taken during an experiment to determine the mechanical equivalent of heat:

Weight of cups, lb	0.330
Weight of water, lb	0 065
Diameter of drum, in	14.0
Room temperature, deg fahr	77.00
Initial temperature of water and cups, deg fahr	63.75
Final temperature of water and cups, deg fahr	90.85
Total revolutions	2000
Specific heat of cup material, Btu per lb per deg fahr	0.094
Value of weight, W, lb	0.272

What would be the value of the mechanical equivalent of heat according to these data?

20b. A saw used to cut marble uses 10 hp. How much water must be supplied per minute at a temperature of 50 deg fahr to keep the work and saw at 80 deg fahr? (One horsepower = 33,000 ft-lb per min.)

20c. How many foot-pounds are required to raise 295 lb of water 150 deg fahr?

20d. How many foot-pounds of work are there in 1 lb of coal containing 14,600 Btu per lb?

20e. If mechanical energy is being transferred into heat energy at the rate of 10 hp, how many Btu per hour will result?

23a. The following data were taken during an experiment to determine the electrical equivalent of heat:

Temperature of room, deg fahr	71.00
Weight of water container, lb	1.58
Specific heat of container material, Btu per lb per deg fahr	0.10
Weight of water used, lb	1.22
Initial water temperature, deg fahr	64.00
Final water temperature, deg fahr	78.00
Duration of test, sec	487.5
Average voltmeter reading, volts	110.0
Average ammeter reading, amperes	0.38

What would the value for the electrical equivalent of heat be as determined from these data?

23b. An incandescent lamp uses 150 watts of electricity, 75 percent of which is given off in heat. How many Btu of heat are thus given off in 1 hr?

23c. How many kilowatt-hours in 1 ton of coal containing 14,200 Btu per lb?

23d. Ten kilowatts equal how many Btu per min?

23e. A waterproofed resistance was placed into a solution of petroleum oil. The current drawn by the resistance was 2.7 amperes and the voltage across it was 100 volts. If the oil weighed 60 lb and the current was left on for 120 min, what temperature change would result if all the electrical energy went into heating the oil?

24a. Given: 1 Btu = 778 ft-lb; 1 Btu = 1055 watt-seconds; 1 hp = 550 ft-lb per sec; 1 kilowatt = 1000 watts, and 1 lb = 453 grams. Using these values find the following:

Energy		Power	
1 ft-lb	= ? watt-seconds	1 ft-lb per min	= ? watts
1 ft-lb	= ? Btu	1 hp	= ? ft-lb per min
1 ft-lb	= ? calories	1 hp	= ? kilowatts
1 hp-hr	= ? ft-lb	1 watt	= ? ft-lb per min
1 hp-hr	= ? Btu	1 Btu per min	= ? watts
1 hp-hr	= ? calories	1 Btu per min	= ? ft-lb per min
1 hp-hr	= ? kw-hr	1 Btu per min	= ? hp
1 watt-second	= ? Btu	1 Btu per min	= ? kilowatts
1 watt-second	= ? calories	1 Btu per min	≐ ? calories per sec
1 kw-hr	= ? watt-seconds		
1 kw-hr	= ? Btu		
1 Btu	= ? calories		

ENERGY TRANSFER PROBLEMS

25a. If the human body gives off 400 Btu per hr, and if as a power plant it has an efficiency of 25 percent, how many Btu per day of 24 hr must be taken into the body to keep the plant itself running?

25b. A producer-gas power plant burns 1.21 lb of coal testing 13,200 Btu per lb for each horsepower-hour delivered by the engine. Find the efficiency of the plant in percentage.

25c. A steam power plant has an efficiency of 8.2 percent and delivers, each 24 hr, 12,400 hp-hr of work. Find the amount of coal, testing 13,800 Btu per lb, that will be used per day.

25d. What is the efficiency of the engine in problem **25b** if 40 percent of the energy in the coal is lost before the producer gas is delivered to the engine?

25e. A steam electric power plant transforms 1 kw-hr of energy from 1.12 lb of coal containing 14,300 Btu per lb. Find the efficiency of this energy transfer process.

25f. How many horsepower-hours should an internal-combustion engine having an efficiency of 22 percent develop per gallon of gasoline? (Btu per pound for gasoline = 20,300.)

25g. How many hours will a 60-hp gasoline engine of 22 percent efficiency run on 10 gal of gasoline of 20,300 Btu per lb heating value?

25h. How many pounds of ethyl alcohol per horsepower-hour are required in an engine of 20 percent efficiency? (Btu per pound for ethyl alcohol = 10,500.)

PROBLEMS ON CALORIMETRY TO BE SOLVED BY METHOD OF MIXTURES

28a. Ten pounds of water at 180 deg fahr is mixed with 7 lb of water at 100 deg fahr. What is the resulting temperature?

28b. A piece of iron weighing 8 lb is heated to 212 deg fahr in boiling water, and then dropped into 5.26 lb of water at 50 deg fahr. The resulting temperature is 75 deg fahr. What is the specific heat of the iron?

28c. A block of copper weighing 3 lb and at a temperature of 212 deg fahr is dropped into 5.4 lb of water at 60 deg fahr. The final temperature of the water is 68 deg fahr. What is the specific heat of the copper?

28d. A 3-lb copper container is at a temperature of 70 deg fahr when 8 lb of water at 200 deg fahr is poured into it. What will be the temperature of the water after equilibrium is reached?

28e. Fifteen pounds of water at 210 deg fahr are poured into a copper vessel weighing $1\frac{1}{2}$ lb and containing 6 lb of water at 55 deg fahr. What is the resulting temperature?

28f. It is desired to find the temperature of a furnace. A piece of fire-clay (specific heat = 0.22 Btu per lb per deg fahr) weighing 4 lb is placed in the furnace until it comes up to the temperature of the furnace. It is then dropped into 20 lb of water at 40 deg fahr. The temperature of the water rises to 120 deg fahr. What is the temperature of the furnace?

28g. A piece of lead at 250 deg fahr is dropped into a calorimeter containing 5 lb of water at 50 deg fahr. The final temperature of the water is 83 deg fahr. The calorimeter weighs 0.75 lb and its specific heat is 0.11 Btu per lb per deg fahr. What is the weight of the lead?

PROBLEMS ON CALORIMETRY TO BE SOLVED BY METHOD OF TOTAL HEATS

29a. Suppose we mix in a tank 40 lb of water at 120 deg fahr, and 60 lb of water at 35 deg fahr; what will be the resulting temperature?

29b. A piece of brass weighing 0.361 lb and at 212 deg fahr is dropped into a copper calorimeter containing 0.69 lb of water at 59 deg fahr. The final temperature of the water and brass is 67.8 deg fahr. Find the specific

heat of the brass, neglecting the heat absorbed by the calorimeter. What would be the specific heat of the brass considering the heat absorbed by the calorimeter, if the calorimeter weighed 0.16 lb?

29c. A lead ball weighing 9 lb, after being raised to a temperature of 212 deg fahr, is dropped into a vessel containing 9.5 lb of water at 49.8 deg fahr. The temperature of the water rises to 54.3 deg fahr. The weight of the vessel is 7 lb and its specific heat = 0.10 Btu per lb per deg fahr. Find the specific heat of the lead.

29d. What was the initial temperature of a 3-lb cast-iron weight when placed in a bucket containing 7.5 lb of water at a temperature of 80 deg fahr if the temperature of the whole became 85 deg fahr? The bucket which held the water weighed 0.75 lb and its specific heat was 0.11 Btu, per lb per deg fahr.

29e. A mixture of 12 lb of aluminum and 50 lb of lead is heated to 212 deg fahr and dropped into a calorimeter containing 2 lb of water at a temperature of 50 deg fahr. The calorimeter weighs 0.80 lb and has a specific heat = 0.095 Btu per lb per deg fahr. What is the final temperature of the mixture?

29f. What is the resulting temperature if 4 lb of brass at 170 deg fahr is placed in 5 lb of water at 50 deg fahr, the water being contained in a crown glass vessel weighing 0.5 lb?

29g. What is the resulting temperature if 10 lb of petroleum oil at 300 deg fahr is mixed with 23 lb of benzine at 70 deg fahr in a silver dish weighing 1.2 lb?

30a. An elementary laboratory calorimeter has a weight of 0.75 lb. If the calorimeter is made of nickel, what is its water equivalent?

30b. A fuel calorimeter is constructed of 2.30 lb of steel, 1.25 lb of nickel, and 0.15 lb of silver. Determine its water equivalent.

PROBLEMS ON CALORIMETRY OF SOLID AND LIQUID FUELS

32a. A 1-gram sample of coal is burned in a bomb calorimeter having a water equivalent of 0.56 lb, and containing 2.08 lb of water. The original temperature of the water was 67.89 deg fahr, and the final temperature of the water was 81.24 deg fahr. What is the Btu per lb of the coal?

32b. A 1-gram sample of coal is burned in a bomb calorimeter which is made of 1.81 lb of copper and 9.35 lb of steel. It contains 10.7 lb of water at 71.4 deg fahr before the coal was burned, and the temperature increases to 74.1 deg fahr by the combustion of the coal. What is the heating value of the coal in Btu per pound?

32c. A sample of benzine weighing 9.07 grams is burned in a bomb calorimeter containing 18.20 lb of water and having a water equivalent of 0.80 lb. The initial temperature of the water was 71.27 deg fahr, and

the final temperature was 91.82 deg fahr. Determine the heating value of benzine in Btu per pound.

PROBLEMS ON CALORIMETRY OF GASEOUS FUELS

33a. A volume of 1.22 cu ft of gas was burned in a Junker calorimeter. During the test 20.5 lb of water passed through the calorimeter. The inlet temperature of the water was 62.1 deg fahr, and the outlet temperature was 91.8 deg fahr. What was the heating value of the gas in Btu per cubic foot, as supplied.

33b. A Junker calorimeter is used to determine the heating value of natural gas. During the test the following data were obtained:

Total number of cubic feet of gas burned.	= 1.8
Total amount of water passed through calorimeter, lb. . .	=49
Inlet temperature of water, deg fahr.	=50
Outlet temperature of water, deg fahr.	=90

Determine the heating value of the gas in Btu per cubic foot, as supplied.

33c. A volume of 3.1 cu ft of gas having a heating value of 560 Btu per cu ft is burned in a Junker calorimeter. If the inlet water temperature is 48 deg fahr and the outlet water temperature is 85 deg fahr, how many pounds of water were passed through the calorimeter during the test?

PROBLEMS ON LINEAR EXPANSION

(Obtain values for the coefficient of linear expansion for various materials from Table II.)

35a. A bar of wrought iron is 100 in. long at 70 deg fahr. If the temperature of the bar is raised to 1000 deg fahr, what increase in length will be produced by this temperature change? What will be the new overall length of the bar?

35b. A 120-ft length of copper trolley wire is used between trolley poles. The temperature change that this wire undergoes is from − 40 deg fahr in the winter to 100 deg fahr in the summer. What will be the change in length of the wire due to this temperature change?

35c. If 50-ft steel rails are laid when the temperature is 40 deg fahr, how much space must be left between each pair, assuming highest summer temperature to be 110 deg fahr?

35d. How much will a 12-ft wrought-iron boiler tube expand in length when heated from 40 deg fahr to 300 deg fahr?

35e. How much will a 300-ft span of a steel bridge vary in length owing to the change from a summer temperature of 110 deg fahr to a winter temperature of − 10 deg fahr?

35f. A steel surveyor's chain 66 ft long at 60 deg fahr is used in zero weather to measure a mile. What length must be added to a measured mile to have a true mile?

35g. An aluminum rod measured 24.5000 in. in length when at a temperature of 70 deg fahr. The rod was heated until it became 24.5061 in. long. To what temperature was the rod heated?

35h. A piece of brass wire is 30 ft long at 50 deg fahr. It expands 0.5724 in. in length when heated to 200 deg fahr. Find the coefficient of linear expansion of brass wire?

PROBLEMS ON AREAL AND CUBICAL EXPANSION

(Necessary coefficients will be found in Table II.)

36a. A sheet tin roof is 30 ft long and 25 ft wide. If it undergoes a temperature change of 40 deg fahr, what will be the increase in area of the tin in square inches?

36b. A strip of concrete pavement is 100 ft long and 30 ft wide. What change in area will occur when this strip of pavement undergoes a temperature change of 50 deg fahr? (Coefficient of linear expansion of concrete = 0.0000080 on the Fahrenheit scale.)

36c. A cylindrical steel boiler is 60 in. in diameter and 180 in. long. What will be the change in surface area of the boiler due to a temperature change of 300 deg fahr?

37a. A block of steel 35 in. long, 22 in. wide, and 8 in. deep is subjected to a temperature change of 300 deg fahr. What will be the change in volume of the block?

37b. If a cubic foot of wrought iron weighs 460 lb at 50 deg fahr, how much will 1 cu ft weigh at 1000 deg fahr?

37c. A volume of 1800 cu in. of glycerine is at a temperature of 70 deg fahr. How many cubic inches would this same amount of glycerine occupy when at a temperature of 200 deg fahr?

37d. What change in volume would result if 20 cu in. of mercury at 40 deg fahr were heated to 250 deg fahr?

37e. A cubic foot of water at 32 deg fahr weighs 62.42 lb. What would a cubic foot of water at 200 deg fahr weigh?

PROBLEMS ON PRESSURE MEASUREMENT

42a. A tank has a bottom area of 50 sq in. and is filled with water to a height of 3 ft. If the water weighs 62.4 lb per cu ft, what will be the weight of water acting downward on each square inch of the bottom area of the tank?

42b. If the tank of problem **42a** were filled with mercury weighing 0.491 lb per cu in., what would be the unit pressure in pounds per square inch acting on the bottom of the tank?

42c. A pump delivers water to a point 200 ft above the pump. Against what pressure in pounds per square inch is the pump working?

42d. A water pump is working against a 250-ft head. What unit pressure is this equivalent to?

42e. A head of 30 in. of mercury would be equivalent to a unit pressure of how many pounds per square inch?

43a. A barometer reads 29.28 in. of mercury. What is the atmospheric pressure in pounds per square inch?

43b. If the atmospheric pressure is 16.2 lb per sq in., what is the barometric reading in inches of mercury?

43c. A barometer is made using gasoline instead of mercury. If gasoline weighs 42.0 lb per cu ft, how high will the gasoline column stand in the barometer tube when the atmospheric pressure is 14.83 lb per sq in.?

43d. If water were used instead of gasoline in problem **43c,** what would be the height of the water column under "standard conditions"?

44a. A vacuum gage attached to a container shows a vacuum of 30 in. of mercury. What is the absolute pressure in pounds per square inch inside the container? If the gage showed a vacuum of 15 in. of mercury, what would be the absolute pressure in the container? If the vacuum gage registered 0 in. of mercury? True barometer reading = 30 in. of mercury.

44b. Under conditions of standard pressure a condenser is operating under an absolute pressure of 5 lb per sq in. If a mercury vacuum gage is attached to this condenser, how many inches of vacuum will it register?

44c. A vacuum of 22 in. of mercury indicates what absolute pressure in the container to which the vacuum gage is attached? Assume conditions of standard atmospheric pressure.

44d. During a condenser test the vacuum gage showed an average reading of 28 in. of mercury. The average barometer reading was 29.5 in. of mercury. What was the average absolute pressure in the condenser during the test?

45a. A Bourdon tube pressure gage shows a pressure of 100.3 lb per sq in. The barometer reading is 29.92 in. of mercury. What is the absolute pressure in the container to which the Bourdon tube gage is attached?

45b. Under "standard conditions" a gage reads 250 lb per sq in. What is the corresponding absolute pressure?

45c. The pressure of the steam in a certain boiler is 150 lb per sq in. gage. The barometer read 28.5 in. of mecrury when the pressure gage was read. What is the absolute boiler pressure?

45d. A tank contains a quantity of air under pressure. A gage attached to the tank reads 140.3 lb per sq in. The barometer reading is 30 in. of mercury. What is the absolute pressure of the air in the tank?

47a. An open-tube manometer connected to a gas main shows a dif-

ference in level of 5 in. of water. The barometer reads 29.4 in. of mercury. What is the absolute pressure of the gas in the main?

47b. If boiled linseed oil weighing 58.8 lb per cu ft were used instead of water in the manometer in problem **47a,** what would be the absolute pressure of the gas if the difference in level was still 5 in.?

47c. A manometer containing castor oil weighing 60.5 lb per cu ft is connected to a gas main and shows a difference in level of 10 in. of oil. The barometer reads 30 in. of mercury. What is the absolute pressure producing the 10-in. difference in level?

PROBLEMS ON BOYLE'S LAW

48a. If 10 cu ft of a gas at a pressure of 40 lb per sq in. abs is reduced to a volume of 5 cu ft, what will be the absolute pressure of the gas?

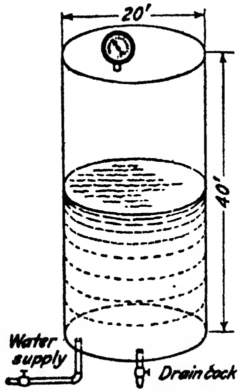


FIG. 48c.—Storage tank.

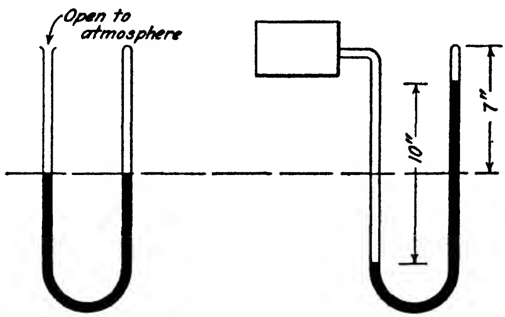


FIG. 48d.—Closed-tube manometer.

48b. If an absolute pressure of 60 lb per sq in. on 30 cu ft of gas is increased to 100 lb per sq in. abs, what will be the corresponding volume?

48c. A cylinder 20 ft in diameter and 40 ft long rests on one end, as shown in Fig. 48c. Water is admitted through a suitable inlet connection at the bottom, compressing the air above the water as indicated by the gage on the top of the tank. Starting with no water in the tank and an air pressure of 14.7 lb per sq in. abs, calculate the corresponding absolute air pressures for water heights above the bottom of the tank of 5 ft, 10 ft, 15 ft, 20 ft, 25 ft, 30 ft, and 35 ft.

Plot a curve with the above calculated absolute air pressures on the vertical axis, and their corresponding air volumes on the horizontal axis.

48d. Fig. 48d shows a closed-end manometer containing mercury. The amount of mercury is so chosen that the column stands to the same height in both legs when the open end is exposed to conditions of standard

atmospheric pressure. When in this position, what is the absolute pressure in the closed tube?

When the open leg of the manometer is connected to a vessel containing air under pressure the mercury column is shifted, becoming lower in the leg attached to the vessel, and higher in the closed leg. Under these conditions is the air over the mercury in the closed tube at a pressure equal to, greater than, or less than the air over the mercury in the other tube? Why? Assume a 10-in. difference in mercury level; what is the absolute pressure in the vessel to which the open leg is connected?

48e. One pound of air at 32 deg fahr and 14.7 lb per sq in. abs occupies a volume of 12.39 cu ft. If this quantity of air is compressed at constant temperature to a volume of 5.00 cu ft, what would be the resulting absolute pressure? Gage pressure?

48f. Two cubic feet of air at standard atmospheric pressure is compressed at constant temperature to a pressure of 80.3 lb per sq in. gage. What is the new volume of the air?

48g. Air is drawn into the cylinder of an air compressor from the atmosphere when the piston is at a distance of 6 in. from the cylinder head of the compressor. The diameter of the compressor piston is 4 in. What would be the absolute pressure of the air when the piston is 1 in. from the cylinder head? The gage pressure?

48h. A cylinder contains a certain volume of gas under a pressure of 200 lb per sq in. abs. How much must the volume be decreased to increase the pressure to 1000 lb per sq in. abs, if the gas temperature remains unaltered?

48i. One cubic foot of gas at 100 lb per sq in. abs expands at constant temperature. What will be the absolute gas pressure when the volume is 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 cu ft? Plot a curve showing the relation of absolute pressure and volume.

48j. If 110 cu in. of atmospheric air is taken inside the cylinder of a gasoline engine during the intake stroke, what volume will this charge occupy when compressed to a pressure of 50 lb per sq in. gage?

PROBLEMS ON ABSOLUTE TEMPERATURE AND CHARLES' LAW

49a. Convert the following Fahrenheit temperatures to the corresponding absolute temperature on the Fahrenheit scale: 0 deg fahr, 32 deg fahr, 180 deg fahr, 212 deg fahr, 1000 deg fahr, − 10 deg fahr, − 300 deg fahr, − 460 deg fahr.

49b. If 3.5 lb of nitrogen has a volume of 43.8 cu ft at 32 deg fahr, what volume will it occupy at 70 deg fahr?

49c. If 72 cu ft of oxygen at 80 deg fahr is heated to 160 deg fahr, what is its new volume?

49d. If 200 cu in. of hydrogen at 75 deg fahr were cooled to 32 deg fahr, what volume would result?

49e. If 60 cu ft of a perfect gas is cooled from a temperature of 212 deg fahr to 70 deg fahr, what will its final volume be?

49f. What is the change in volume when 100 lb of air is heated from 32 deg fahr to 170 deg fahr at atmospheric pressure? (One cubic foot of air at 32 deg fahr weighs 0.0807 lb at atmospheric pressure.)

49g. What is the change in volume when 100 lb of dry air is cooled from 200 deg fahr to 70 deg fahr at atmospheric pressure? (One cubic foot of dry air at 200 deg fahr weighs 0.06018 lb.)

49h. A bubble of air formed at the bottom of a lake increased to 8 times its original volume in traveling to the water surface. How many feet deep was the lake at this point? Assume 14.7 lb per sq in. for atmospheric pressure.

49i. At a certain point in a lake the water is 200 ft deep. If a gas bubble were released at the bottom of the lake at this point, what would be the percentage increase in the volume of the bubble when it arrived at the water surface?

49j. A certain automobile engine has a 3.5-in. bore and a 5-in. stroke. The clearance volume is 15 percent of the total piston displacement. When the piston is at the bottom of its stroke the pressure in the cylinder is that of the atmosphere. What is the pressure of the gas-air mixture confined in the cylinder when the piston is at the top of its stroke? (Assume constant temperature throughout stroke.)

PROBLEMS ON THE GENERAL GAS LAW EQUATION

50a. If 200 cu ft of air at 14.7 lb per sq in. abs pressure and 70 deg fahr are pumped into a tank of 10 cu ft capacity, what will be the temperature of the air in the tank when the pressure reaches 300 lb per sq in. abs?

50b. A given weight of gas occupies 10 cu ft at 200 deg fahr and 70 lb per sq in. gage. What volume will the same gas occupy under "standard conditions"?

50c. Eight pounds of oxygen at atmospheric pressure and 32 deg fahr occupy 89.6 cu ft. How many cubic feet would 6 lb of oxygen at 30 lb per sq in. gage and 70 deg fahr occupy?

50d. A storage tank contains 12 cu ft of oxygen at 100.3 lb per sq in. gage and 70 deg fahr. How many cubic feet of oxygen would this be under "standard conditions"?

50e. An air compressor pumps 100 cu ft of air from a room at 78 deg fahr. The compressor delivers the air at a pressure of 100 lb per sq in. gage to an air heater where its temperature is raised to 400 deg fahr. What is the final volume of the air?

50f. A gasoline engine having a clearance volume equal to 18 percent of the piston displacement draws in a charge of gas and air from the atmosphere at 70 deg fahr. When the charge is compressed into the clearance space the pressure becomes 160 lb per sq in. abs. What is the resulting temperature of the charge under full compression? Assume that upon intake the charge occupies both the clearance and displacement volumes.

50g. In problem **50f,** after the charge is exploded in the cylinder the temperature becomes 3300 deg fahr. What is the pressure then?

50h. In problem **50g,** at the end of the expansion stroke the pressure becomes 40 lb per sq in. abs. What is the corresponding temperature?

51a. An automobile tire holds air at 70 deg fahr and 35 lb per sq in. gage pressure. If the tire is allowed to stand in the sun until its temperature becomes 90 deg fahr, what will be the resulting gage pressure if the tire does not change in volume?

51b. A tank contains air at 50 deg fahr and 150 lb per sq in. gage. To what temperature must the tank be heated to produce a gas pressure of 200 lb per sq in. gage?

PROBLEMS ON GASES INVOLVING THE WEIGHT OF THE GAS

(Necessary gas densities and values of R are given in Table III.)

53a. A tank contains 10 cu ft of a permanent gas under a pressure of 100.3 lb per sq in. gage. The temperature of the gas is 70 deg fahr. If $R = 60$, what is the weight of the gas?

53b. A tank has a capacity of 15 cu ft. It is filled with acetylene at a pressure of 60 lb per sq in. abs and a temperature of 60 deg fahr. What is the weight of acetylene contained in the tank?

53c. Discuss the equation $PV = WRT$, explaining each symbol and the units in which it is expressed.

53d. Devise an experiment to determine the value of R for a given gas.

53e. If 10.7 lb of sulphur dioxide are contained in a tank of 10 cu ft capacity a gas pressure of 100 lb per sq in. abs results. The temperature of the gas is 100 deg fahr. What is the value of R for sulphur dioxide?

53f. A tank having a capacity of 12 cu ft contains air under atmospheric pressure and at 65 deg fahr. Air is pumped into the tank until the pressure becomes 150.3 lb per sq in. gage, and the gas temperature increases to 78 deg fahr. What weight of air was pumped into the tank?

54a. If 100 lb of carbon dioxide is contained in a closed tank of 500 cu ft capacity, what is the density of carbon dioxide under these conditions?

54b. The density of air under standard conditions as given in Table III is 0.0807 lb per cu ft. How much would 70 cu ft of air under standard conditions weigh?

54c. Calculate the density of 1 lb of air under normal atmospheric pressure when the temperature is 90 deg fahr.

54d. What is the density of dry air at 85 deg fahr and 60 lb per sq in. abs pressure?

PROBLEMS ON FUSION

57a. What quantity of heat is required to completely melt 1 lb of ice at 32 deg fahr into water at 32 deg fahr? For 1 lb of copper?

57b. What quantity of heat is required to completely melt 8 lb of ice at 32 deg fahr into water at 32 deg fahr?

57c. If 100 lb of ice at 20 deg fahr is changed into water at 32 deg fahr, how many Btu were supplied? (Specific heat of ice = 0.5.)

57d. If 80 lb of ice at 15 deg fahr is changed into water at 120 deg fahr, how many Btu were supplied?

57e. What quantity of heat is required to convert 125 lb of copper at 70 deg fahr into molten copper? (Melting temperature of copper = 1064 deg fahr; specific heat of copper = 0.0933.)

57f. How many pounds of ice at 32 deg fahr will it take to cool 45 lb of water from 110 deg fahr to 43 deg fahr?

57g. A piece of ice weighs 112 lb. If 5760 Btu are applied to the ice, what percentage of it by weight will be melted? Initial temperature of ice = 30 deg fahr.

57h. If 3000 Btu are supplied to 11 lb of ice at 14 deg fahr, what will be the resulting temperature?

DRILL PROBLEMS ON QUANTITIES OF HEAT

(Involving both fusion and evaporation at atmospheric pressure. Specific heat of ice = 0.5; specific heat of steam = 0.48.)

65a. What quantity of heat is required to raise:

1 lb of water from 33 deg fahr to 43 deg fahr?
5 lb of water from 45 deg fahr to 50 deg fahr?
4 lb of water from 95 deg fahr to 110 deg fahr?
3 lb of ice from − 10 deg fahr to 16 deg fahr?
563 lb of ice from − 9 deg fahr to − 3 deg fahr?
20 lb of ice from − 6 deg fahr to 4 deg fahr?
13 lb of ice from 4 deg fahr to 10 deg fahr?
112 lb of ice from 20 deg fahr to 25 deg fahr?
30 lb of ice from 25 deg fahr to 32 deg fahr?
50 lb of ice from 20 deg fahr to 33 deg fahr?
80 lb of ice from 27 deg fahr to 45 deg fahr?
15 lb of water from 200 deg fahr to 212 deg fahr?
18 lb of water from 180 deg fahr to 213 deg fahr (at atmospheric pressure)?
20 lb of water from 195 deg fahr to 220 deg fahr (at atmospheric pressure)?

596 lb of water from 32 deg fahr to 225 deg fahr (at atmospheric pressure)?

124 lb of ice from − 10 deg fahr to 250 deg fahr (at atmospheric pressure)?

118 lb of ice from 25 deg fahr to 260 deg fahr (at atmospheric pressure)?

65b. What quantity of heat is given up when:

3 lb of water are lowered from 100 deg fahr to 95 deg fahr?

5 lb of steam at atmospheric pressure are lowered from a temperature of 215 deg fahr to 213 deg fahr?

The temperature of 10 lb of steam at atmospheric pressure is lowered from 220 deg fahr to 200 deg fahr?

50 lb of steam at atmospheric pressure is changed from 260 deg fahr to ice at 10 deg fahr?

80 lb of steam at atmospheric pressure is changed from 250 deg fahr to ice at − 8 deg fahr?

65c. How many Btu are given up when the temperature of 5 lb of water is lowered from 62 deg fahr to freezing? How many pounds of ice at 32 deg fahr must be melted to water at 32 deg fahr to absorb this amount of heat?

65d. If 2 lb of ice at 32 deg fahr are put into 5 lb of water at 62 deg fahr, what will be the resulting temperature? How much water will there be when the temperature reaches 32 deg fahr? How much ice?

65e. Four pounds of water at 200 deg fahr drops 1 deg fahr in temperature. How much heat does it give up in doing so?

65f. If a colder body absorbs 100 Btu from 4 lb of water at 200 deg fahr, what is the resulting temperature of the water?

65g. If 1 lb of ice at 32 deg fahr is placed in a very light container, and submerged in 4 lb of water at 200 deg fahr, what will be the temperature of the water at the instant the ice melts, assuming that the water equivalent of the container is negligible and that all the water resulting from the melting of the ice is at a temperature of 32 deg fahr?

If this pound of water at 32 deg fahr is poured into the 4 lb of water, what will be the resulting temperature?

What is the resulting temperature when 3 lb of ice at 32 deg fahr are allowed to melt in 10 lb of water at 180 deg fahr?

65h. How much heat is required to convert 1 lb of ice at 32 deg fahr into water at 35 deg fahr?

65i. How much ice at 32 deg fahr must be put into 4 gal of water at 75 deg fahr to result in water at 35 deg fahr?

65j. In the previous problem, what was the percentage increase in volume when the ice was added?

65k. How much ice at 32 deg fahr is required to make 1 qt of iced tea

at 36 deg fahr if the tea was originally at 212 deg fahr and all the cooling is done with cracked ice?

65l. How much heat is given up by 1 lb of steam at atmospheric pressure when converted into water at 90 deg fahr?

65m. How much steam at atmospheric pressure is required to give up 700 Btu when reduced to water at 90 deg fahr?

65n. How many Btu are required to raise 500 lb of water from 60 deg fahr to 90 deg fahr?

65o. How much saturated steam at 212 deg fahr must be condensed in 500 lb of water at 60 deg fahr to raise the temperature to 90 deg fahr?

65p. How much steam at atmospheric pressure is required to convert 500 lb of snow at 0 deg fahr into water at 40 deg fahr, the steam condensing and mixing with the water from the melting snow?

65q. A block of ice at 0 deg fahr and weighing 100 lb is dropped into a tank containing 9000 lb of water at 32 deg fahr, and allowed to remain until its temperature rises to 32 deg fahr. How many pounds of water remain in the tank?

Will a 1000-lb cake of ice necessarily lose weight on a foggy morning, even though the temperature of the air is above 32 deg fahr?

65r. How many Btu are necessary to convert 1 lb of water at 212 deg fahr into steam at 212 deg fahr and normal atmospheric pressure? 2 lb of water? 8 lb of water? 142 lb of water?

65s. A tea-kettle contains 5 lb of water at 60 deg fahr. What quantity of heat will be required to boil away all the water? Assume conditions of normal atmospheric pressure.

65t. A radiator uses 35 lb of dry steam at atmospheric pressure in 1 hr. If the condensed water leaves the radiator at a temperature of 150 deg fahr, how many Btu does the radiator give off per hour?

65u. If the process of heating water in an open vessel on a coal stove is 75 percent efficient, how many pounds of water can be evaporated with 1 lb of coal having a heating value of 14,000 Btu per lb? Initial temperature of the water = 56 deg fahr. Assume normal atmospheric pressure.

65v. A 22-lb cake of ice would require how many pounds of coal to melt it and change the resulting water into steam at 212 deg fahr? Coal liberates 14,300 Btu per lb.

65w. What quantity of heat is required to convert 5 lb of water at 65 deg fahr into steam at 500 deg fahr and atmospheric pressure. (Specific heat of steam = 0.48.)

65x. If coal contains 2 percent moisture, how much does this effect the heat available from the coal if the fuel is stoked at 80 deg fahr, and the flue gases have a temperature of 560 deg fahr? Express the result in Btu lost per pound of coal fired. (Specific heat of steam = 0.48.)

65y. If coal as fired into a furnace contains 5 percent moisture and has a heating value of 13,300 Btu per lb, how much of the energy is required

to evaporate this 5 percent of water if the coal is fired at 75 deg fahr, and the flue gases escape from the furnace at a temperature of 620 deg fahr? (Specific heat of steam = 0.48.)

68a. A certain still delivers 12 lb of ethyl alcohol into the receiving vessel per hour. The circulating water for the condenser enters at a temperature of 55 deg fahr and leaves at a temperature of 135 deg fahr. The alcohol leaves the condenser at 70 deg fahr. Taking the latent heat of alcohol as 369 Btu per lb, its boiling point as 160 deg fahr, and its specific heat as 0.59, what is the rate of flow of water through the condenser in pounds per hour?

68b. How many pounds of circulating water will be required to condense 10 lb of ethyl alcohol to a temperature of 100 deg fahr, if the temperature of the tap water is 60 deg fahr, and the outlet water from the condenser is at 90 deg fahr? Use physical properties of alcohol given in problem **68a.**

PROBLEMS ON THE USE OF STEAM TABLES

72a. From the steam tables (Table V) find the temperature at which evaporation takes place when water is heated under the following surface pressures: 14.7 lb per sq in. abs, 42 lb per sq in. abs, 66 lb per sq in. abs, 100 lb per sq in. gage, 330 lb per sq in. abs, 972.3 lb per sq in. gage. (Barometer = 29.92 in. of mercury.)

72b. At what temperature would water boil when under the following vacuums: 24 in. of mercury, 20 in. of mercury, 10 in. of mercury, 4 in. of mercury, 0.8 in. of mercury? (Barometer = 30 in. of mercury.)

72c. What is the volume occupied by 1 lb of dry steam when under a pressure of 14.7 lb per sq in. abs? At 50 lb per sq in. abs? At 100.3 lb per sq in. gage?

72d. If 5 lb of steam is confined under a pressure of 56 lb per sq in. abs and 288.2 deg fahr, what volume does it occupy?

73a. How many Btu are required to heat 1 lb of water from 32 deg fahr to boiling when subjected to the following surface pressures: 14.7 lb per sq in. abs, 30 lb per sq in. abs, 150.3 lb per sq in. gage, 1200 lb per sq in. abs.

74a. In problem **73a,** how many Btu would be required to convert the pound of water from the evaporation temperature completely into dry steam for each case given?

75a. Calculate the external latent heat supplied during the generation of 1 lb of dry steam at a pressure of 150 lb per sq in. abs. (Specific volume of water at 360 deg fahr is 0.01816 cu ft per lb.)

76a. In problem **74a,** what is the total heat that has been added to the water at 32 deg fahr to convert it into dry steam for each case?

76b. If 150 lb of water at 32 deg fahr is heated until it is entirely con-

verted into steam, how many Btu are supplied if the steam pressure is 200 lb per sq in. abs?

76c. Steam is generated in a boiler in which the pressure gage reads 100.3 lb per sq in. The barometer reads 29.92 in. of mercury. Find the following physical properties of the steam:

1. Volume occupied by 1 lb of dry steam.
2. Heat of liquid per pound of steam.
3. Total heat per pound of dry steam.
4. Internal latent heat per pound of dry steam.
5. Total latent heat per pound of dry steam.

76d. Find the number of Btu required to heat 1 lb of water from 120 deg fahr to the evaporation temperature when the pressure is 44 lb per sq in. abs. (Assume specific heat of water = 1.000.)

76e. Find the heat in Btu required to raise the temperature of 1 lb of water to the boiling point when under the absolute pressure of 110, 164, 240, and 322 lb per sq in. Water temperature = 76 deg fahr before the application of heat.

76f. Find the total quantity of heat required to convert an entire pound of water into dry and saturated steam at 80 lb per sq in. abs pressure. Water supplied to boiler at 120 deg fahr.

76g. Water is fed to a boiler at a temperature of 180 deg fahr. The boiler generates dry steam at a gage pressure of 120.3 lb per sq in. Barometer reads 29.92 in. of mercury. How many Btu are required to form 235 lb of steam?

76h. A steam boiler evaporates 47,300 lb of water per hour into dry steam. Gage pressure = 237 lb per sq in. Atmospheric pressure = 14.6 lb per sq in. Feedwater temperature = 220 deg fahr. How much heat was supplied to the water in an hour? If the boiler efficiency is 72 percent, how many pounds of coal per hour containing 14,200 Btu per lb must be burned in the furnace?

PROBLEMS ON QUALITY OF STEAM

77a. Steam is generated having a quality of 98 percent. The gage on the boiler reads 100.3 lb per sq in.; atmospheric pressure is 14.7 lb per sq in. How many Btu were supplied to each pound of steam? Water supplied to boiler at 32 deg fahr.

77b. Find the total heat, above 32 deg fahr, in a pound of wet steam having a quality of 99 percent at the following absolute pressures: 60, 130, 160, 110, 210, and 250 lb per sq in.

77c. Solve problem **77b**, finding the total heat per pound of wet steam above 250 deg fahr.

77d. The total heat above 32 deg fahr in 1 lb of steam at 200 lb per sq in. abs pressure is 1180 Btu. What is the quality of the steam?

77e. A steam boiler evaporates 10 lb of water per lb of coal. If the steam receives 10,000 Btu per lb of coal burned, what is the quality of the steam if it is at an absolute pressure of 150 lb per sq in., and the water is fed to the boiler at a temperature of 200 deg fahr?

77f. During the test of a steam boiler the following data were taken:

Pounds of water evaporated in 12 hr = 467,100 lb.
Steam gage reading = 252 lb per sq in.
Barometer reading = 28.92 in. of mercury.
Feedwater temperature = 314 deg fahr.
Quality of steam = 98.5 percent.

How many Btu were delivered to the water per hour?

77g. One pound of dry and saturated steam is compressed from a pressure of 100 lb per sq in. abs to a pressure of 250 lb per sq in. abs without the addition or subtraction of any heat from the steam. What is the quality of the steam at the higher pressure?

77h. One pound of steam at 30 lb per sq in. abs pressure is expanded to atmospheric pressure without a change in its total heat content. When at atmospheric pressure the steam is dry and saturated. What was the initial quality of the steam at the higher pressure?

PROBLEMS ON SUPERHEATED STEAM

78a. A pound of steam is superheated 100 deg fahr, and is at a pressure of 150 lb per sq in. abs. What is its temperature?

78b. A boiler generates steam at 230 lb per sq in. abs. The temperature of the steam as it leaves the boiler is 470 deg fahr. Is this steam wet, dry, or superheated? What is its quality? Degree of superheat?

78c. Fill in the last column in the following table by calculating the total heat per pound of superheated steam in each case:

Absolute steam pressure, lb per sq in.	Temperature of steam, deg fahr	Total heat per pound of steam, Btu
55.0	300	
85.0	350	
104.0	420	
180.0	450	
220.0	550	
300.0	600	

78d. Steam is generated at a gage pressure of 250 lb per sq in.; atmospheric pressure is 14.6 lb per sq in.; feedwater temperature 280 deg fahr; superheat 135 deg fahr. How many Btu are contained in 8 lb of the steam formed?

78e. A boiler supplies a steam main at 190 lb per sq in. abs, and at 450 deg fahr. What is the total heat per pound of steam as it enters the main?

PROBLEMS ON STEAM CALORIMETERS

82a. Develop an equation for calculating the quality of steam by means of a throttling calorimeter. Explain the meaning of each symbol.

82b. A throttling calorimeter is attached to a steam main containing steam under a pressure of 100 lb per sq in. gage. After the steam passes through the orifice of the calorimeter, its temperature is 256 deg fahr. Calorimeter discharges to the atmosphere. Barometer reading 30.55 in. of mercury. What is the quality of the steam in the steam main?

82c. The following data were taken from a throttling calorimeter in the determination of the quality of steam coming from a boiler:

Steam pressure before the orifice = 140 lb per sq in. gage.
Steam pressure after the orifice = 5 lb per sq in. gage.
Temperature of steam after orifice = 268.0 deg fahr.
Barometer reading = 30.55 in. of mercury.

What was the quality of the steam coming from the boiler?

82d. Steam at 120 lb per sq in. gage and at 100 percent quality is passed through a throttling calorimeter which is discharging to the atmosphere. The barometer reads 29.92 in. of mercury. Find the following:

(1) Temperature of steam before passing through orifice.
(2) Temperature of steam after passing through orifice.
(3) Total heat per pound of steam after passing orifice.

82e. Repeat problem **82d,** with steam at 160 lb per sq in. gage and the quality at 97 percent.

86a. Explain the principle of operation of the separating calorimeter.

86b. The following data were obtained from a 10-min test with a separating calorimeter:

Total weight of dry steam exhausted from calorimeter = 2.75 lb.
Total weight of moisture separated from supplied steam = 0.25 lb.

Find the quality of the steam tested.

87a. A separating calorimeter is attached to a steam main in which the pressure is 100 lb per sq in. abs. If the area of the calorimeter orifice is

0.035 sq in., and the moisture collected in 10 minutes is 0.20 lb, what is the quality of the steam in the main? (Solve by means of Napier's equation.)

87b. The following data were obtained from a separating calorimeter when used to determine the quality of steam being supplied to a steam engine:

Duration of test = 7 min.
Total weight of moisture separated = 0.10 lb.
Pressure of steam in calorimeter = 30 lb per sq in. abs.
Diameter of calorimeter orifice = 0.133 in.

Determine the quality of the steam.

PROBLEMS ON CONDUCTION

(Consult Table VI for necessary values of K.)

91a. A steel plate $\frac{7}{8}$ in. thick is exposed to a temperature of 70 deg fahr on one side, while the temperature on the other side is 250 deg fahr. What quantity of heat flows through each square foot of this sheet in an hour's time?

91b. A cylindrical steel boiler 60 in. in diameter and 20 ft long is generating steam at a temperature of 320 deg fahr. If the boiler plate is $\frac{1}{2}$ in. thick, how many Btu are conducted through it hourly? Temperature of room is 75 deg fahr.

91c. A plate glass store window is 20 ft long and 8 ft high and $\frac{1}{4}$ in. thick. How many Btu per hour are conducted through this window when the store temperature is 78 deg fahr and the outside temperature 40 deg fahr?

91d. The walls of a certain refrigerator have an area of 32 sq ft, and are made of corkboard 2 in. thick. What quantity of heat will pass through the walls in a day of 24 hr if the room temperature is 78 deg fahr and the refrigerator temperature is 40 deg fahr? How many pounds of ice per day would be melted in this refrigerator?

91e. A steam pipe carrying dry steam at 200.3 lb per sq in. gage pressure is 100 ft in length. If the outside diameter of pipe is 6.625 in., and the inside diameter 6.065 in., how many Btu are conducted through the pipe hourly? Room temperature = 82 deg fahr; K = 240.0.

91f. How many Btu per hour will pass through a brick wall 22 ft high, 40 ft long, and 8 in. thick if the temperature difference between faces of the wall is 42 deg fahr?

How many pounds of coal of 13,200 Btu per lb heating value would have to be burned to compensate for this heat loss in a day? Assume K = 4.0.

91g. How many tons of ice per day would be melted in an 80 ft by 40 ft by 40 ft ice house? Walls and roof contain 8 in. thickness of sawdust, and outside temperature is 80 deg fahr. Neglect heat loss through ground.

PROBLEMS ON HEAT FLOW THROUGH COMPOSITE WALLS

(Assume slight movement of air in air space between walls.)

93a. Calculate the value of U for a wall constructed of an 8-in. thickness of brick and a 2-in. thickness of fir.

93b. Compute the value of U for a wall constructed of a 6-in. thickness of concrete, a $\frac{1}{2}$-in. thickness of pine, and a $\frac{1}{2}$-in. thickness of "Celotex." (c for "Celotex" = 1.50.)

93c. Compute the value of U for a wall constructed of 1-in. thickness of maple, 3-in. air space, 1-in. thickness of pine, and $\frac{1}{2}$-in. thickness of plaster. (Consider the air in the air space to be in motion.)

93d. Calculate the value of U for a wall constructed of an 8-in. thickness of brick, a 3-in. air space, and a 2-in. thickness of pine board. What would the value of U for this wall become if the inside pine wall were covered with a $\frac{1}{2}$-in. thickness of "Celotex"?

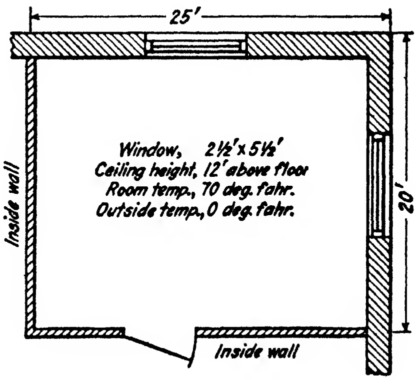


FIG. 94a.—Plan view of room.

93e. The walls of a certain refrigerator are made up of layers of material in the following order:

$\frac{7}{8}$ in. matched pine boards
One thickness of waterproof paper
$\frac{7}{8}$ in. matched pine boards
3-in. thickness of corkboard
$\frac{7}{8}$ in. matched pine boards
One thickness of waterproof paper
$\frac{7}{8}$ in. matched pine boards

Neglecting the insulating effect of the waterproof paper, determine the value of U for the refrigerator wall.

94a. The room shown in Fig. 94a has an outside wall constructed of

8 in. of brick, a 4-in. air space, 1-in. thickness of pine, and $\frac{1}{2}$-in. thickness of "Celotex." The windows are double hung and are $2\frac{1}{2}$ ft wide and $5\frac{1}{2}$ ft high; the ceiling of the room is 12 ft above the floor. Thickness of window glass = $\frac{1}{8}$ in. Determine the quantity of heat that is transmitted through the outside wall per hour.

94b. A 6-in. steam main, carrying steam at 175 lb per sq in. abs pressure in a room at 70 deg fahr, has a total surface area of 180 sq ft. If the main is insulated with a thickness of 2 in. of magnesia, what is the total heat loss in Btu per hour for the entire surface?

PROBLEMS ON CONVECTION

100a. A hot-water boiler circulates 700 lb of water per hr through the radiators and piping of a certain house. If the house receives 60,000 Btu per hr from the heating system, and the water leaves the boiler at a temperature of 200 deg fahr, what is the temperature of the water when it returns to the boiler?

100b. An instantaneous hot-water heater heats 4.23 lb of water per cu ft of illuminating gas burned. If the water is heated from a temperature of 50 deg fahr, what is its final temperature if the gas burned has a heating value of 550 Btu per cu ft?

100c. A chimney exhausts 8250 lb of gaseous material at 600 deg fahr in an hour; the temperature of the outside air is 76 deg fahr; specific heat of chimney gases is 0.24. How many Btu per hour pass up the chimney?

100d. A schoolroom 30 ft long, 25 ft wide, and 12 ft high receives air at a temperature of 100 deg fahr from a hot-air register. If the heat loss from the room is 12,000 Btu per hr, and the air returns to the heating system at a temperature of 65 deg fahr, how many pounds of air must be supplied to the room every hour by the heating system? (Specific heat of air = 0.238.)

100e. For every pound of coal burned under a steam boiler, 12 lb of gaseous products pass up the chimney at a temperature of 600 deg fahr; find the quantity of heat carried up the chimney for every pound of coal burned. Temperature of incoming air is 65 deg fahr; specific heat of flue gases is 0.237 Btu per lb per deg fahr.

PROBLEMS ON COMBUSTION

118a. How many pounds of oxygen are required to burn 1 lb of carbon to carbon dioxide? To carbon monoxide?

119a. How many pounds of oxygen are required to burn 1 lb of sulphur to sulphur dioxide? What is the weight of the sulphur dioxide produced?

120a. How many pounds of oxygen are required to burn 1 lb of hydrogen? What is the product of combustion? How much will it weigh?

120b. A substance upon being analyzed was found to contain 5 parts by weight of hydrogen. If all this hydrogen was in combination with oxygen in the form of water, how many parts of water would there be present?

120c. A substance contains a total of 30 parts by weight of hydrogen, a portion of this hydrogen being in combination with oxygen in the form of water. If the substance contains 5 parts by weight of water, how many parts of free hydrogen are present?

120d. In Dulong's equation for the heating value of a solid fuel, what does the expression $(H - O/8)$ become if a sample has 4 parts hydrogen and just sufficient oxygen to form water? Is this true in every case where there is no hydrogen other than that in the moisture? What does the expression $(H - O/8)$ represent?

PROBLEMS ON HEATING VALUE OF SOLID FUELS

121a. A sample of coal selected from the bunkers in a certain power plant gave the following ultimate analysis in percent by weight: carbon 68.69, hydrogen 4.84, oxygen 11.49, sulphur 1.01, nitrogen 1.54. Calculate the heating value of this coal by means of Dulong's equation.

121b. Calculate the heating value in Btu per pound of the coals given in the following table:

Carbon	Hydrogen	Oxygen	Sulphur	Nitrogen	Ash
70.7	4.87	8.70	0.95	1.38	13.40
74.1	4.15	6.50	1.25	1.45	12.55
75.3	4.17	6.10	1.29	1.54	11.60
41.3	6.77	40.80	0.96	0.65	9.52
60.1	5.89	27.04	0.60	1.06	5.31
80.6	4.58	4.67	1.00	1.84	7.61
80.3	3.62	3.60	1.75	1.47	9.26

121c. The ultimate analysis of a Pennsylvania anthracite "as fired" is: sulphur 0.46, hydrogen 2.52, carbon 78.85, nitrogen 0.77, and oxygen 5.87. Calculate the heating value of this anthracite in Btu per pound "as fired."

121d. A Florida peat yields the following ultimate analysis: sulphur 0.50, hydrogen 6.14, carbon 47.87, nitrogen 2.89, oxygen 36.20. Determine the heating value by means of Dulong's equation.

121e. What is the heating value of a Colorado lignite yielding the

following ultimate analysis: sulphur 0.22, hydrogen 5.75, carbon 47.70, nitrogen 0.64, and oxygen 35.56?

123a. Define the term higher heating value. Lower heating value.

124a. Determine the heating value of a fuel on an "as received" basis which has the following proximate analysis:

Volatile combustible	=32 percent
Fixed carbon	=56 percent
Moisture	= 3 percent
Ash	= 9 percent

124b. Determine the heating value on a moisture-free basis for the coal tested in problem **124a.**

125a. How many pounds of air must pass through a furnace to supply 1 lb of oxygen? How many cubic feet of air at atmospheric pressure and 70 deg fahr are required? (Consult Table VIII, Appendix B.)

125b. How many pounds of air are required to burn 3 lb of carbon to carbon monoxide? To carbon dioxide? How many cubic feet of air would be required in each case? Assume atmospheric pressure and a temperature of 70 deg fahr.

125c. Compute the weight of air required to burn the following:

1000 lb of carbon to CO
1000 lb of carbon to CO_2
5 tons of carbon to CO_2
30 lb of hydrogen to water vapor.

Also compute the Btu evolved in each case.

125d. Compute the theoretical weight of air required per pound of coal for the perfect combustion of an anthracite having the following ultimate analysis: carbon 88.86, hydrogen 2.05, nitrogen 0.90, oxygen 1.94, sulphur 0.35, and ash 5.90.

125e. A Western bituminous coal yields the following ultimate analysis on an "as fired" basis: carbon 54.60, hydrogen 5.48, nitrogen 1.10, oxygen 21.53, sulphur, 4.00, and ash 13.29. Calculate the theoretical amount of air in pounds that will be required for the combustion of 1 ton of this coal. If the combustion takes place with 50 percent excess air, how many pounds of air will be supplied per pound of coal?

PROBLEMS ON RELATIVE HUMIDITY

150a. The word relative signifies a ratio. What is its significance in connection with the term relative humidity?

150b. What is saturated air? How does an increase in temperature affect its degree of saturation?

150c. A cubic foot of air at 70 deg fahr contains 2 grains' weight of moisture. What is the absolute humidity of the air under these conditions?

150d. If a cubic foot of air at a certain temperature contains 2 grains of moisture, what is its relative humidity if it is capable of holding 3 grains per cubic foot at this temperature? 4 grains per cubic foot? 2 grains per cubic foot?

152a. From Table XVIII find the percentage of relative humidity when the dry-bulb temperature is 70 deg fahr and the wet-bulb temperature is 61 deg fahr.

152b. From Table XVIII find the percentage of relative humidity when the dry-bulb temperature is 75 deg fahr and the wet-bulb depression is 14 deg.

152c. The relative humidity in a certain room is known to be 47 percent. By Table XVIII, what would be the wet-bulb temperature if the room temperature is 69 deg fahr?

152d. From values obtained from Table XVIII, plot a curve showing the relation between dry-bulb temperatures (on the horizontal axis) and wet-bulb temperatures (on the vertical axis) for a constant relative humidity of 50 percent. Dry-bulb temperatures range from 60 deg fahr to 80 deg fahr.

154a. Determine the percentage of relative humidity by use of the Psychrometric Chart for the following conditions:

Dry-Bulb Temperature deg fahr	Wet-Bulb Temperature deg fahr
40	35
50	42
60	53
70	62
80	65
90	73
100	80

154b. A sling psychrometer gave the following readings when in use: dry-bulb temperature 73 deg fahr; wet-bulb temperature 61 deg fahr. Determine the percentage of relative humidity and the dew point by means of the Psychrometric Chart.

154c. What are the dew-point temperature and wet-bulb temperature corresponding to a dry-bulb temperature of 85 deg fahr and a relative humidity of 50 percent?

154d. What are the relative humidity and wet-bulb temperature corresponding to a dry-bulb temperature of 70 deg fahr and a dew point of 37 deg fahr?

154e. Find the dry-bulb temperature and dew point when the relative humidity is 50 percent and the wet-bulb temperature 58.5 deg fahr.

154f. Find the dry-bulb temperature and relative humidity when the wet-bulb temperature is 60 deg fahr and the dew point 49 deg fahr.

154g. Find the dry-bulb temperature and wet-bulb temperature when the relative humidity is 45 percent and the dew point at 53 deg fahr.

PROBLEMS ON HOUSEHOLD HUMIDIFICATION

(To be solved by means of the curves in Fig. 63.)

157a. What quantity of water should be evaporated per day in a well-built house of 17,000 cu ft capacity in order to maintain the humidity at 45 percent when the inside temperature is 70 deg fahr? Relative humidity of outside air 60 percent; temperature of outside air 5 deg fahr.

157b. What quantity of water would have to be evaporated per day in problem **157a** if the temperature of the outside air was 20 deg fahr and the outside relative humidity 70 percent?

157c. It is desired to maintain conditions of 45 percent relative humidity and 70 deg fahr in a house of 20,000 cu ft capacity which has 1.5 air changes per hour. If the outside air is at 10 deg fahr and the outside relative humidity is 75 percent, what quantity of water must be evaporated in the house per day?

157d. If the evaporation of the water in problem **157c** is accomplished by means of a water-pan type of humidifier, what hourly quantity of heat will be required? Water supplied to the evaporating pan at 60 deg fahr.

157e. Find the quantity of heat that must be supplied hourly to a water-pan type of humidifier in order to evaporate a sufficient amount of water to produce a relative humidity of 45 percent in 10-deg weather for a house of 11,000 cu ft capacity and of normal construction. Assume a complete air change once per hour. Relative humidity of outside air = 55 percent. Water supplied to humidifier at 55 deg fahr.

WORK DIAGRAM PROBLEMS

159a. A steam locomotive moves a train through a horizontal distance of 500 ft by exerting a constant drawbar pull of 2000 lb. Draw a work diagram expressing the amount of work done by the locomotive.

159b. Plot a work diagram for the following set of conditions: A body moving 5 ft against a resistance of 5 lb, then 10 ft against a resistance of 7 lb, and finally 15 ft more against a resistance of 10 lb. (Total distance traveled by body = 30 ft.)

159c. A centrifugal pump delivers 500 gal of water against a total pressure of 120 lb per sq in. Plot a work diagram showing the quantity

of work done by the pump, using horizontal distances to represent pounds and vertical distances feet.

159d. An elevator weighing 2100 lb carries a load of $\frac{1}{2}$ ton through a vertical distance of 30 ft. Represent the work done by means of a work diagram.

159e. A tractor hauls a load through a distance of 400 ft. The resistance offered to motion at various parts of the travel were as follows:

Distance traveled, ft	Resistance, lb
0	200
50	220
100	250
150	230
200	260
250	300
300	280
350	210
400	250

Assuming the resistance to vary uniformly between readings, determine the amount of work done by the tractor in traveling the 400 ft. (Plot a work diagram and determine its area.)

160a. A force of 200 lb is required to compress a spring through a distance of 4 in. If the force required to compress the spring varies directly with its deformation, how much work is done in compressing it through 9 in.? Show graphically.

PROBLEMS ON EXPANSION OF GASES

162a. Twenty-five cubic feet of air is expanded at a constant pressure of 150 lb per sq in. abs to a volume of 125 cu ft. Calculate the quantity of work done by the air. State answer both in inch-pounds and foot-pounds. What quantity of heat does this represent? (778 ft-lb = 1 Btu.)

162b. What amount of heat is required to double the volume of a cubic foot of air if the pressure remains constant at 75 lb per sq in. abs? What quantity of heat would be required to triple the volume of a given quantity of air at normal atmospheric pressure?

162c. A gas is compressed in such a manner that its pressure remains constant. The initial volume is 60 cu ft and the final volume is 10 cu ft. If the pressure maintained is 110 lb per sq in. abs, what quantity of work is done in compressing the gas? Show this graphically by means of a pressure-volume diagram.

163a. If the expansion in problem **162a** had taken place at constant temperature instead of at constant pressure, what would be the pressure

of the gas at the end of expansion? What quantity of work would the gas perform in expanding? What quantity of heat does this represent?

163b. A given weight of air is expanded isothermally from an initial pressure of 95 lb per sq in. abs to normal atmospheric pressure. The initial volume is 2 cu ft. Find the following:

(*a*) Final volume of air,
(*b*) Quantity of work done during expansion,
(*c*) Heat equivalent of (*b*).

164a. Ten cubic inches of air is expanded adiabatically from 150 lb per sq in. abs and 400 deg fahr to a pressure of 20 lb per sq in. abs. Find:

(*a*) The volume of the air at end of expansion.
(*b*) The work done during expansion.
(*c*) What quantity of heat did the air absorb?
(*d*) What will be the resulting temperature at the end of the expansion?

164b. Solve problem **164a,** using ammonia instead of air.

164c. What quantity of work is delivered by 25 cu ft of air at 65 lb per sq in. abs and 200 deg fahr in expanding adiabatically to normal atmospheric pressure? What will be the resulting temperature at the end of the expansion?

164d. An air compressor receives air from a room at 65 deg fahr and compresses it adiabatically to a pressure of 97.3 lb per sq in. gage. What would be the temperature of the air after compression?

164e. The initial temperature of 20 cu in. of a gas at 14.7 lb per sq in. abs is 75 deg fahr. When the gas is compressed adiabatically to a pressure of 120 lb per sq in. abs, its temperature becomes 400 deg fahr. Determine the value of n for this gas.

164f. Plot the pressure-volume diagram for 1 lb of air expanded isothermally at a temperature of 400 deg fahr. On the same axes plot the adiabatic curve for the expansion of 1 lb of air. Use a pressure range from (0 to 100) lb per sq in. abs. Measure the areas under these curves and interpret these in terms of work done. Check work done by proper equations.

PROBLEMS ON ENTROPY

167a. Fill in the blank columns in the following table from the Steam Tables:

Pressure, lb per sq in. abs.	Entropy of water, θ	Entropy of evaporation, L/T	Entropy of dry and saturated steam, ϕ
50			
75			
100			
125			
150			
175			
200			
300			
400			

167b. What is the change in entropy when 1 lb of a substance having a specific heat of 0.13 is heated from 50 to 200 deg fahr?

167c. Determine the change in entropy when 1 lb of air is heated from 60 to 150 deg fahr at constant pressure. At constant volume.

167d. Plot the temperature-entropy diagram for the heating of 1 lb of water from 32 to 212 deg fahr. Determine the values of the entropy in eighteen 10-deg steps using the true values of the specific heat of water as given in Fig. 5.

PROBLEMS TO BE SOLVED WITH TOTAL HEAT-ENTROPY DIAGRAM (Fig. 74)

170a. Steam is taken from a steam main at a pressure of 140 lb per sq in. abs and expanded through the orifice of a throttling calorimeter to a pressure of 14.7 lb per sq in. abs. If the superheat on the atmospheric side of the orifice is 50 deg fahr, determine the quality of the steam in the main. Check your answer by calculating the quality by the method described in Chapter V.

170b. Fifteen pounds of steam is expanded at constant entropy from a pressure of 100 lb per sq in. abs and 200 deg fahr superheat to normal atmospheric pressure. Determine the quality of the steam at the end of expansion and the total quantity of heat converted into work. How many foot-pounds of work are delivered?

170c. An engine cylinder contains 0.8 lb of steam at 200 lb per sq in.

abs and 300 deg fahr of superheat. If the steam expands at constant entropy to a pressure of 40 lb per sq in. abs, how many foot-pounds of work are accomplished? What is the condition of the steam at the end of expansion? (State quality or superheat.)

170d. Ten pounds of dry steam is expanded at a constant pressure of 250 lb per sq in. abs to a condition of 94 percent quality. What is the total quantity of heat delivered by the steam? What quantity of work does this represent? What is the total change in entropy during this process?

170e. What quantity of heat is required to convert 12 lb of steam at 30 lb per sq in. abs and 98 percent quality to a condition of 200 lb per sq in. abs and 400 deg of superheat?

170f. What quantity of work in foot-pounds was done on the steam in problem **170e**?

170g. What quantity of heat is supplied when 1 lb of steam is expanded at a constant pressure of 120 lb per sq in. abs from a condition of 96 percent quality to one of 500 deg of superheat? What is the change in entropy that takes place?

170h. Find the amount of heat necessary to superheat 500 lb of dry and saturated steam 200 deg at a pressure of 170 lb per sq in. abs.

APPENDIX B

MISCELLANEOUS TABLES

Table I

USEFUL NUMBERS

$$\pi = 3.1416 = \frac{22}{7} = \frac{\text{circumference}}{\text{diameter}}$$

$$\pi^2 = 9.8696; \frac{1}{\pi} = 0.3183 = \frac{7}{22}$$

$$\text{Area of circle} = \pi r^2 = \frac{\pi d^2}{4} = 0.7854d^2 = \frac{11}{14}d^2$$

$$\text{Surface of cyl.} = 2\pi rl + 2\pi r^2$$

$$\text{Volume of cyl.} = \pi r^2 l$$

$$\text{Surface of sphere} = 4\pi r^2$$

$$\text{Volume of sphere} = \frac{\pi d^3}{6} = \frac{4\pi r^3}{3}$$

METRIC–ENGLISH EQUIVALENTS

1 cm	=	0.39 in.	1 in.	=	2.54 cm
1 m	=	39.37 in.	1 ft	=	30.48 cm
1 m	=	3.28 ft	1 ft	=	0.305 m
1 km	=	0.6 mi	1 mi	=	1.609 km
1 gm	=	0.035 oz (avoir.)	1 oz	=	28.35 gm
1 kg	=	2.204 lb (avoir.)	1 lb	=	453.6 gm
1 sq cm	=	0.155 sq in.	1 sq in.	=	6.45 sq cm
1 cu cm	=	0.061 cu in.	1 cu in.	=	16.39 cc
1 liter	=	0.2642 gal, U.S.	1 gal, U.S.	=	3.785 liters
1 liter	=	0.2200 gal, British	1 gal, British	=	4.546 liters

UNITS OF FORCE, WORK, POWER, ETC.

1 dyne = 0.00102 gm
1 ft-lb = 1.356×10^7 ergs
1 joule = 10^7 ergs
1 watt = 10^7 ergs/sec = 1 joule/sec

MECHANICAL EQUIVALENTS OF HEAT

1 gm of water heated 1 deg cent = 4.2×10^7 ergs
1 lb of water heated 1 deg cent = 1400 ft-lb
1 lb of water heated 1 deg fahr = 780 ft-lb
780 ft-lb = 1 Btu
4.2×10^7 gm = 1 calorie (= 4.2 joules)
4.28×10^4 gr-cm = 1 calorie (= 4.2 joules)
4.2 watt-seconds = 1 calorie (= 4.2 joules)

(For a complete table showing the relation between the various units, see Table II.)

Table II

EQUIVALENT VALUES OF ELECTRICAL, MECHANICAL, AND HEAT-UNITS

From Kent's "Mechanical Engineers' Handbook"

Work Units

Unit	Equivalent Value in Other Units
1 kw-hr =	1,000 watt-hours. 1.34 hp-hr. 2,654,200 ft-lb. 3,600,000 joules. 3,412 heat-units (Btu). 367,000 kg-m. 0.235 lb carbon oxidised with perfect efficiency. 3.52 lb water evap. from and at 212 deg fahr. 22.75 lb of water raised from 62 to 212 deg fahr.
1 hp-hr =	0.746 kw-hr. 1,980,000 ft-lb. 2,545 heat-units (Btu). 273,740 kg-m. 0.175 lb carbon oxidised with perfect efficiency. 2.64 lb water evap. from and at 212 deg fahr. 17.0 lb water raised from 62 to 212 deg fahr.
1 joule =	1 watt-second. 0.000000278 kw-hr. 0.102 kg-m. 0.0009477 heat-units (Btu). 0.7373 ft-lb.
1 ft-lb =	1.356 joules. 0.1383 kg-m. 0.000000377 kw-hr. 0.001285 heat-unit (Btu). 0.0000005 hp-hr.
1 kg-m =	7.233 ft-lb. 0.00000365 hp-hr. 0.00000272 kw-hr. 0.0093 heat-unit (Btu).

Power Units

Unit	Equivalent Value in Other Units
1 kw =	1,000 watts. 1.34 hp. 2,654,200 ft-lb per hr. 44,240 ft-lb per min. 737.3 ft-lb per sec. 3,412 heat-units per hr. 56.9 heat-units per min. 0.948 heat-unit per sec. 0.253 lb carbon oxidized per hr. 3.52 lb water evap. per hr from and at 212 deg fahr.
1 hp =	746 watts. 0.746 kw. 33,000 ft-lb per min. 550 ft-lb per sec. 2,545 heat-units per hr. 42.4 heat-units per min. 0.707 heat-unit per sec. 0.175 lb carbon oxidized per hr. 2.64 lb of water evap. per hr from and at 212 deg fahr.
1 watt =	1 joule per sec. 0.00134 hp. 3.412 heat-units per hr. 0.7373 ft-lb per sec. 0.0035 lb water evap. per hour from and at 212 deg fahr. 44.24 ft-lb per min. 1 lb pull at half a mile per hour (approx.).
1 watt per sq in. =	8.19 heat-units per sq ft per min. 6,371 ft-lb per sq ft per min. 0.193 hp per sq ft.

Heat-Units, Work

Unit	Equivalent Value in Other Units
1 heat-unit =	1 British Thermal Unit. Symbol, Btu. 252 calories.
1 heat-unit Btu =	1,055 watt-seconds. 780 ft-lb. 107.6 kg-m. 0.000293 kw-hr. 0.000393 hp-hr. 0.0000688 lb carbon oxidised. 0.001036 lb water evap. from and at 212 deg fahr.
1 lb carbon oxidized with perfect efficiency =	14,544 heat-units. 1.11 lb anthracite coal oxidized. 2.5 lb dry wood oxidized. 21 cu ft illuminating gas. 4.26 kw-hr. 5.71 hp-hr. 11,315,000 ft-lb. 15 lb of water evap. from and at 212 deg fahr.
1 lb water evap. from and at 212 deg fahr =	0.283 kw-hr. 0.379 hp-hr. 970 heat-units. 103,900 kg-m. 1,019,000 joules. 751,300 ft-lb. 0.0664 lb of carbon oxidized.

Heat Units, Power

Unit	Equivalent Value in Other Units
1 heat-unit per sq ft per min =	0.122 watt per sq in. 0.0176 kw per sq ft. 0.0236 hp per sq ft.

TABLE III

STANDARD FIXED POINTS USED IN THERMOMETRY

Substance	Transformation	Temperature	
		Degrees Centigrade	Degrees Fahrenheit
Oxygen	Boiling point	−182.98	−297.36
Carbon bisulphide	Melting point	−112.0	−169.6
Carbon dioxide	Boiling point	−78.5	−109.3
Mercury	Melting point	−38.88	−37.98
Water	Melting point	0.00	32.00
Water	Boiling point	100.00	212.00
Naphthalene	Boiling point	217.95	424.31
Tin	Melting point	231.9	494.4
Benzophenone	Boiling point	305.9	582.6
Cadmium	Melting point	320.9	609.6
Zinc	Melting point	419.4	786.9
Sulphur	Boiling point	444.55	832.19
Antimony	Melting point	630.0	1166.0
Aluminum	Melting point	658.7	1217.7
Silver	Melting point	960.2	1760.4
Gold	Melting point	1062.6	1944.7
Copper	Melting point	1082.8	1981.0
Lithium metasilicate	Melting point	1201.0	2293.8
Diopside	Melting point	1391.5	2536.7
Nickel	Melting point	1452.6	2646.7
Palladium	Melting point	1549.5	2821.1
Platinum	Melting point	1755.0	3191.0

N.B.—The boiling points are at standard pressure.

Table IV

APPROXIMATE MELTING POINTS OF METALS

Metal	Temperature, Degrees Fahrenheit	Metal	Temperature, Degrees Fahrenheit
Wrought iron	2737	Lead	621
Pig iron (gray)	2190–2327	Bismuth	520
Cast iron (white)	2075	Tin	449
Steel	2460–2550	Platinum	3191
Steel (cast)	2500	Gold	1945
Copper	1981	Silver	1760
Zinc	786	Aluminum	1218
Antimony	1166		

Table V

TEMPERATURE AND APPEARANCE OF FLAME *

Appearance of Flame	Temperature, Degrees Fahrenheit	Appearance of Flame	Temperature, Degrees Fahrenheit
Dark red	975	Deep orange	2010
Dull red	1290	White	2370
Dull cherry red	1470	Bright white	2550
Full cherry red	1650	Dazzling white	2730
Clear cherry red	1830		

* C. S. M. Pouillet.

Table VI

VOLUME AND WEIGHT OF DISTILLED WATER AT VARIOUS TEMPERATURES *

Temperature, Degrees Fahrenheit	Relative Volume Water at 39.2 Deg = 1	Weight per Cubic Foot, Pounds	Temperature, Degrees Fahrenheit	Relative Volume, Water at 39.2 Deg = 1	Weight per Cubic Foot, Pounds	Temperature, Degrees Fahrenheit	Relative Volume Water at 39.2 Deg = 1	Weight per Cubic Foot, Pounds	Temperature, Degrees Fahrenheit	Relative Volume Water at 39.2 Deg = 1	Weight per Cubic Foot, Pounds
32	1.000176	62.42	160	1.02337	61.00	290	1.0830	57.65	430	1.197	52.2
39.2	1.000000	62.43	170	1.02682	60.80	300	1.0890	57.33	440	1.208	51.7
40	1.000004	62.43	180	1.03047	60.58	310	1.0953	57.00	450	1.220	51.2
50	1.00027	62.42	190	1.03431	60.36	320	1.1019	56.66	460	1.232	50.7
60	1.00096	62.37	200	1.03835	60.12	330	1.1088	56.30	470	1.244	50.2
70	1.00201	62.30	210	1.04256	59.88	340	1.1160	55.94	480	1.256	49.7
80	1.00338	62.22	212	1.04343	59.83	350	1.1235	55.57	490	1.269	49.2
90	1.00504	62.11	220	1.0469	59.63	360	1.1313	55.18	500	1.283	48.7
100	1.00698	62.00	230	1.0515	59.37	370	1.1396	54.78	510	1.297	48.1
110	1.00915	61.86	240	1.0562	59.11	380	1.1483	54.36	520	1.312	47.6
120	1.01157	61.71	250	1.0611	58.83	390	1.1573	53.94	530	1.329	47.0
130	1.01420	61.55	260	1.0662	58.55	400	1.167	53.5	540	1.35	46.3
140	1.01705	61.38	270	1.0715	58.26	410	1.177	53.0	550	1.37	45.6
150	1.02011	61.20	280	1.0771	57.96	420	1.187	52.6	560	1.39	44.9

* Marks and Davis.

Table VII

EFFECT OF ALTITUDE IN REDUCING THE BOILING POINT OF WATER

Altitude, Feet	Barometer at 32 Deg Fahr, Inches	Boiling Point, Degrees Fahrenheit	Atmospheric Pressure, Pounds per Square Inch	Altitude, Feet	Barometer at 32 Deg Fahr, Inches	Boiling Point, Degrees Fahrenheit	Atmospheric Pressure, Pounds per Square Inch
0	29.92	212	14.70	8,000	22.38	198	10.98
500	29.43	211	14.46	8,500	21.96	197	10.78
1000	28.93	210	14.21	9,000	21.55	196	10.58
1500	28.44	209	13.97	9,500	21.15	195	10.38
2000	27.94	209	13.72	10,000	20.75	194	10.19
2500	27.44	208	13.48	10,500	20.36	193	10.00
3000	26.94	207	13.23	11,000	19.98	192	9 81
3500	26.44	206	12.99	11,500	19 60	191	9.63
4000	25.95	205	12.75	12,000	19.24	191	9.45
4500	25.47	204	12.52	12,500	18.88	190	9.27
5000	25.01	203	12.29	13,000	18.52	189	9.09
5500	24.55	202	12.06	13,500	18.17	188	8.92
6000	24.09	201	11.83	14,000	17.82	187	8.75
6500	23.65	200	11.61	14,500	17.47	186	8.58
7000	23.22	199	11.39	15,000	17.12	185	8.41
7500	22.80	199	11.18	15,500	16.77	184	8.24

Table VIII

VOLUME AND WEIGHT OF AIR

AT ATMOSPHERIC PRESSURE

Temperature, Degrees Fahrenheit	Volume One Pound, Cubic Foot	Weight per Cubic Foot, Pound	Temperature, Degrees Fahrenheit	Volume One Pound, Cubic Foot	Weight per Cubic Foot, Pound	Temperature, Degrees Fahrenheit	Volume One Pound, Cubic Foot	Weight per Cubic Foot, Pound
32	12.390	0.080710	160	15.615	0.064041	340	20.151	0.049625
50	12.843	.077863	170	15.867	.063024	360	20.655	.048414
55	12.969	.077107	180	16.119	.062039	380	21.159	.047261
60	13.095	.076365	190	16.371	.061084	400	21.663	.046162
65	13.221	.075637	200	16.623	.060158	425	22.293	.044857
70	13.347	.074923	210	16.875	.059259	450	22.923	.043624
75	13.473	.074223	212	16.925	.059084	475	23.554	.042456
80	13.599	.073535	220	17.127	.058388	500	24.184	.041350
85	13.725	.072860	230	17.379	.057541	525	24.814	.040300
90	13.851	.072197	240	17.631	.056718	550	25.444	.039302
95	13.977	.071546	250	17.883	.055919	575	26.074	.038352
100	14.103	.070907	260	18.135	.055142	600	26.704	.037448
110	14.355	.069662	270	18.387	.054386	650	27.964	.035760
120	14.607	.068460	280	18.639	.053651	700	29.224	.034219
130	14.859	.067299	290	18.891	.052935	750	30.484	.032804
140	15.111	.066177	300	19.143	.052238	800	31.744	.031502
150	15.363	.065092	320	19.647	.050898	850	33.004	.030299

Table IX

ELEMENTS AND COMPOUNDS ENCOUNTERED IN COMBUSTION

Substance	Molecular Symbol	Atomic Weight		Molecular Weight		Form
		Accurate	Approximate	Accurate	Approximate	
Carbon	C *	12 005	12	†	......	Solid
Hydrogen	H_2	1 008	1	2.015	2	Gas
Oxygen	O_2	16 00	16	32.00	32	Gas
Sulphur	S_2	32.07	32	64.14	64	Solid
Nitrogen ‡	N_2	14 01	14	28.02	28	Gas
Carbon monoxide	CO	......	......	28.01	28	Gas
Carbon dioxide	CO_2	......	......	44.01	44	Gas
Methane	CH_4	......	......	16.03	16	Gas
Acetylene	C_2H_2	......	......	26.03	26	Gas
Ethylene	C_2H_4	......	......	28.03	28	Gas
Ethane	C_2H_6	......	......	30.05	30	Gas
Sulphur dioxide	SO_2	......	......	64.07	64	Gas
Hydrogen sulphide	H_2S	......	......	34.08	34	Gas
Water vapor	H_2O	......	......	18 02	18	Vapor
Air	....	......	......	28.94	29	Gas

* Atomic symbol.

† The molecular weight of C has not been definitely determined. Carbon exists in a number of forms each of which probably has its own molecular weight. The latest investigations indicate that a molecule of carbon in any form consists of at least 12 atoms.

‡ Atmospheric nitrogen as distinguished from chemically pure nitrogen, which has an atomic weight slightly less than 14.01.

Table X

IGNITION TEMPERATURES

Combustible Substance	Molecular Symbol	Ignition Temperature, Degrees Fahrenheit
Sulphur	S_2	470
Fixed carbon—bituminous coal	....	766
Fixed carbon—semi-bituminous coal	....	870
Fixed carbon—anthracite coal	....	925
Acetylene	C_2H_2	900
Ethane	C_2H_6	1000
Ethylene	C_2H_4	1022
Hydrogen	H_2	1130
Methane	CH_4	1202
Carbon monoxide	CO	1210

TABLE XI

HEAT OF COMBUSTION

BY CALORIMETRIC DETERMINATION

Combustible	Molecular Symbol	Heat Value—Btu per lb		Per Cubic Foot†
		Higher	Lower or Net*	Higher
Hydrogen	H_2	62,000	52,920	348
Carbon (to CO)	C	4,380		
Carbon (to CO_2)	C	14,540		
Carbon monoxide	CO	4,380	....	342
Carbon in CO ‡	C	10,160		
Methane	CH_4	23,850	21,670	1073
Acetylene	C_2H_2	21,460	21,020	1590
Ethylene	C_2H_4	21,450	20,420	1675
Ethane	C_2H_6	22,230	20,500	1883
Sulphur (to SO_2)	S_2	4,050		
Sulphur (to SO_3)	S_2	5,940		

* There is a considerable discrepancy between lower heat values as given by different authorities, the variation being due to methods of computation and assumptions. (See text.) The values given are those of G. A. Goodenough.

† At 32 deg fahr and atmospheric pressure.

‡ Per pound of carbon in carbon monoxide, i.e., 2.33 lb of CO.

TABLE XII

COMBUSTION DATA

IN TERMS OF POUNDS PER POUND OF FUEL

	Molecular Symbol	Theoretically Required, Pounds		Products of Combustion, Pounds				
		O_2	Air	CO_2	H_2O	N_2	CO	SO_2
Carbon (to CO_2)	C	2.667	11.52	3.667	...	8.85		
Carbon (to CO)	C	1.333	5.76	....	...	4.43	2.333	
Carbon monoxide	CO	0.572	2.46	1.57	...	1.89		
Sulphur	S	1.000	4.32	....	...	3.32	....	2.00
Hydrogen	H_2	8.000	34.56	....	9.00	26.56		
Methane	CH_4	4.000	17.28	2.75	2.25	13.28		
Acetylene	C_2H_2	3.077	13.29	3.39	0.69	10.21		
Ethylene	C_2H_4	3.429	14.81	3.14	1.29	11.38		
Ethane	C_2H_6	3.733	16.13	2.93	1.80	12.40		
Hydrogen sulphide	H_2S	1.412	6.10	....	0.53	4.69	....	1.88

Table XIII

SPECIFIC GRAVITY AND WEIGHT IN POUNDS PER GALLON OF FUEL OIL HAVING THE GIVEN BAUMÉ (A. P. I.) READINGS AT 60 DEG FAHR

Degrees Baumé (A. P. I.)	Specific Gravity at 60 Deg Fahr	Pounds per Gallon	Degrees Baumé (A. P. I.)	Specific Gravity at 60 Deg Fahr	Pounds per Gallon
10 0	1.0000	8.331	22.5	0.9188	7.655
10.5	0.9965	8.302	23.0	0.9159	7.630
11.0	0.9930	8.273	23.5	0.9129	7.605
11.5	0.9895	8.244	24.0	0.9100	7.581
12.0	0.9861	8.215	24.5	0.9071	7.557
12.5	0.9826	8.186	25.0	0.9042	7.533
13.0	0.9792	8.158	26.0	0.8984	7.485
13.5	0.9759	8.130	27.0	0.8927	7.437
14.0	0.9725	8.102	28.0	0.8871	7.390
14.5	0.9692	8.074	29.0	0.8816	7.345
15.0	0.9659	8.047	30.0	0.8762	7.300
15.5	0.9626	8.019	31.0	0.8708	7.255
16.0	0.9593	7.992	32.0	0.8654	7.210
16.5	0.9561	7.965	33.0	0.8602	7.166
17.0	0.9529	7.939	34.0	0.8550	7.123
17.5	0.9497	7.912	35.0	0.8498	7.080
18.0	0.9465	7.885	36.0	0.8448	7.038
18.5	0.9433	7.859	37.0	0.8398	6.996
19.0	0.9402	7.833	38.0	0.8348	6.955
19.5	0.9371	7.807	39.0	0.8299	6.914
20.0	0.9340	7.781	40.0	0.8251	6.874
20.5	0.9309	7.755	41.0	0.8203	6.834
21.0	0.9279	7.730	42.0	0.8156	6.795
21.5	0.9248	7.705	43.0	0.8109	6.756
22.0	0.9218	7.680	44.0	0.8063	6.717

TABLE XIV

TYPICAL ANALYSES (BY VOLUME) AND CALORIFIC VALUES OF NATURAL GAS FROM VARIOUS LOCALITIES

Locality of Well	H	CH_4	CO	CO_2	N	O	Heavy Hydro-carbons	H_2S	Btu per Cubic Foot Calculated
Anderson, Ind.....	1.86	93.07	0 73	0.26	3.02	0 42	0.47	0.15	1017
Marion, Ind......	1.20	93.16	0.60	0.30	3.43	0.55	0.15	0.20	1009
Muncie, Ind.......	2.35	92.67	0.45	0.25	3.53	0.35	0.25	0.15	1004
Olean, N. Y......	...	96.50	0.50	....	....	2.00	1.00	.. .	1018
Findlay, Ohio.....	1.64	93.35	0.41	0.25	3.41	0.39	0.35	0.20	1011
St. Ive, Pa........	6.10	75.54	Trace	0.34	....	....	18.12	....	1117
Cherry Tree, Pa...	22.50	60.27	....	2.28	7.32	0.83	6.80	...	842
Grapeville, Pa.....	24.56	14.93	Trace	Trace	18.69	1.22	40.60	....	925
Harvey Well, Butler Co., Pa......	13.50	80.00	Trace	0.66	....	....	5.72	....	998
Pittsburgh, Pa.....	9.64	57.85	1.00	...	23.41	2.10	6.00	....	748
Pittsburgh. Pa....	20.02	72.18	1.00	0.80	....	1.10	4.30	....	917
Pittsburgh, Pa.....	26 16	65.25	0 80	0.60	...	0 80	6.30	.. .	899

Table XV

AREA OF CIRCLES

Diam.	Area	Diam.	Area	Diam.	Area	Diam.	Area
$\frac{1}{8}$	0.0123	$10\frac{1}{2}$	86.59	32	804.24	68	3631.6
$\frac{1}{4}$	0.0491	11	95.03	33	855.30	69	3739.2
$\frac{3}{8}$	0.1104	$11\frac{1}{2}$	103.86	34	907.92	70	3848.4
$\frac{1}{2}$	0.1963	12	113.09	35	962.11	71	3959.2
$\frac{5}{8}$	0.3067	$12\frac{1}{2}$	122.71	36	1017.8	72	4071.5
$\frac{3}{4}$	0.4417	13	132.73	37	1075.2	73	4185.3
$\frac{7}{8}$	0.6013	$13\frac{1}{2}$	143.13	38	1134.1	74	4300.8
1	0.7854	14	153.93	39	1194.5	75	4417.8
$1\frac{1}{8}$	0.9940	$14\frac{1}{2}$	165.13	40	1256.6	76	4536.4
$1\frac{1}{4}$	1.227	15	176.71	41	1320.2	77	4656.0
$1\frac{3}{8}$	1.484	$15\frac{1}{2}$	188.69	42	1385.4	78	4778.3
$1\frac{1}{2}$	1.767	16	201.06	43	1452.2	79	4901.6
$1\frac{5}{8}$	2.073	$16\frac{1}{2}$	213.82	44	1520.5	80	5026.5
$1\frac{3}{4}$	2.405	17	226.98	45	1590.4	81	5153.0
$1\frac{7}{8}$	2.761	$17\frac{1}{2}$	240.52	46	1661.9	82	5281.0
2	3.141	18	254.46	47	1734.9	83	5410.6
$2\frac{1}{4}$	3.976	$18\frac{1}{2}$	268.80	48	1809.5	84	5541.7
$2\frac{1}{2}$	4.908	19	283.52	49	1885.7	85	5674.5
$2\frac{3}{4}$	5.939	$19\frac{1}{2}$	298.64	50	1963.5	86	5808.8
3	7.068	20	314.16	51	2042.8	87	5944.6
$3\frac{1}{4}$	8.295	$20\frac{1}{2}$	330.06	52	2123.7	88	6082.1
$3\frac{1}{2}$	9.621	21	346.36	53	2206.1	89	6221.1
$3\frac{3}{4}$	11.044	$21\frac{1}{2}$	363.05	54	2290.2	90	6361.7
4	12.566	22	380.13	55	2375.8	91	6503.8
$4\frac{1}{2}$	15 904	$22\frac{1}{2}$	397.60	56	2463.0	92	6647.6
5	19.635	23	415.47	57	2551.7	93	6792.0
$5\frac{1}{2}$	23.758	$23\frac{1}{2}$	433.73	58	2642.0	94	6939.7
6	28.274	24	452.39	59	2733.9	95	7088.2
$6\frac{1}{2}$	33.183	$24\frac{1}{2}$	471.43	60	2827.4	96	7238.2
7	38.484	25	490.87	61	2922.4	97	7389.8
$7\frac{1}{2}$	44.178	26	530.93	62	3019.0	98	7542.9
8	50.265	27	572.55	63	3117.2	99	7697.7
$8\frac{1}{2}$	56.745	28	615.75	64	3216.9	100	7854.0
9	63.617	29	660.52	65	3318.3	101	8011.8
$9\frac{1}{2}$	70.882	30	706.86	66	3421.2	102	8171.3
10	78.54	31	754.76	67	3525.6	103	8332.3

Table XVI

TRIGONOMETRIC FUNCTIONS

Angle	Sin	Cos	Tan	Angle	Sin	Cos	Tan
0	0.000	1.000	0.000				
1	.017	.999	.017	46	0.719	0.695	1.04
2	.035	.999	.035	47	.731	.682	1.07
3	.052	.999	.052	48	.743	.669	1.11
4	.070	.998	.070	49	.755	.656	1.15
5	.087	.996	.087	50	.766	.643	1.19
6	.105	.995	.105	51	.777	.629	1.23
7	.122	.993	.123	52	.788	.616	1.28
8	.139	.990	.141	53	.799	.602	1.33
9	.156	.988	.158	54	.809	.588	1.38
10	.174	.985	.176	55	.819	.574	1.43
11	.191	.982	.194	56	.829	.559	1.48
12	.208	.978	.213	57	.839	.545	1.54
13	.225	.974	.231	58	.848	.530	1.60
14	.242	.970	.249	59	.857	.515	1.66
15	.259	.966	.268	60	.866	.500	1.73
16	.276	.961	.287	61	.875	.485	1.80
17	.292	956	.306	62	.883	.469	1.88
18	.309	.951	.325	63	.891	.454	1.96
19	.326	.946	.344	64	.898	.438	2.05
20	.342	.940	.364	65	.906	.423	2.14
21	.358	.934	.384	66	.914	.407	2.25
22	.375	.927	.404	67	.921	.391	2.36
23	.391	.921	.424	68	.927	.375	2.48
24	.407	.914	.445	69	.934	.358	2.61
25	.423	.906	.466	70	.940	.342	2.75
26	.438	.898	.488	71	.946	.326	2.90
27	.454	.891	.510	72	.951	.309	3.08
28	.469	.883	.532	73	.956	.292	3.27
29	.485	.875	.554	74	.961	.276	3.49
30	.500	.866	.577	75	.966	.259	3.73
31	.515	.857	.601	76	.970	.242	4.01
32	.530	.848	.625	77	.974	.225	4.33
33	.545	.839	.649	78	.978	.208	4.70
34	.559	.829	.675	79	.982	.191	5.14
35	.574	.819	.700	80	.985	.174	5.67
36	.588	.809	.727	81	.988	.156	6.31
37	.602	.799	.754	82	.990	.139	7.12
38	.616	.788	.781	83	.993	.122	8.14
39	.629	.777	.810	84	.995	.105	9.51
40	.643	.766	.839	85	.996	.087	11.43
41	.656	.755	.869	86	.998	.070	14.30
42	.669	.743	.900	87	.999	.052	19.08
43	.682	.731	.933	88	.999	.035	28.64
44	.695	.719	.966	89	.999	.017	57.28
45	.707	.707	1.000	90	1.000	.000	Infinity

Table XVII

SPECIFIC GRAVITY OF VARIOUS SUBSTANCES

Solids		Liquids	
Aluminum	2.67	Alcohol	0.79
Brass (cast)	8.38	Benzine	0.69
Copper (cast)	8.85	Chloroform	1.52
Glass	2.63	Ether	0.73
Ice	0.92	Gasoline	0.72
Iron (gray, cast)	7.09	Kerosene	0.80
Iron (wrought)	7.78	Naphtha	0.75
Lead	11.40	Mercury	13.59
Monel metal (rolled)	8.96	Turpentine	0.86
Nickel	8.55	Water (pure)	1.00
Tin (cast)	7.29	Water (sea)	1.03
Zinc (cast)	7.11		

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